AD/A-004 080

REFLECTANCE AND EMITTANCE OF SELECTED MATERIALS AND COATINGS

Martin Donabedian

Aerospace Corporation

Prepared for:

Space and Missile Systems Organization

13 January 1975

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: SAMSO-TR-75-24	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): REFLECTANCE AND EMITTANCE OF SELECTED MATERIALS AND COATINGS	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER: TR-0075(5484)-2
7. AUTHOR(s): M. Donabedian	8. CONTRACT OR GRANT NUMBER(s): F04701-74-C-0075
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The Aerospace Corporation, El Segundo, Calif. 90245	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Space and Missile Systems Organization, Los Angeles Air Force Station, Los Angeles, Calif. 90045	12. REPORT DATE: 13 January 1975
	13. NUMBER OF PAGES: 57
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

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infrared signatures	directional reflectance	solar cells
solar absorptance	directional emittance	second surface mirrors
spectral reflectance	aluminum	black paints
spectral emittance	titanium	anodized aluminum
hemispherical emittance	white paints	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A literature review was made to provide the reflective and thermal radiative properties (emittance) of a number of selected materials and surface coatings applicable to a few specific satellites. With the data provided, the infrared radiation signature for each surface may be evaluated from both a spectral and directional basis. Properties defined include solar absorptance, normal and hemispherical emittance, spectral reflectance and emittance, and directional (angular) reflectance and emittance. Pertinent data which aid in predicting degradation of the solar absorptance in the space environment

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 KEY WORDS (Continued)

20 ABSTRACT (Continued)

are also presented. The selected materials include aluminum alloy 6061, titanium alloy 6Al-4V, beryllium, various titanium dioxide and zinc oxide pigmented (white) coatings, solar cells, optical solar reflectors (second surface mirrors), using both rigid and flexible substrates, black pigmented coatings, and clear and black anodized aluminum coatings.

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PREFACE

This report documents research initiated by The Aerospace Corporation's Space Defense Directorate of the Technology Division and carried out by the Vehicle Engineering Division. It should be clearly emphasized that this report is not intended as a general reference for radiative and optical properties of materials. Rather, it represents a compilation of only selected materials and properties organized solely for use as a preliminary guide in a specific AF study wherein one of the purposes is to evaluate signatures of selected satellites.

CONTENTS

TABLES

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FIGURES

FIGURES (Continued)

I. INTRODUCTION

In order to predict the infrared signature (i.e., unique emission characteristics) of a particular spacecraft it is necessary to obtain certain basic properties of external spacecraft surfaces. All satellite materials exhibit reflectance and emittance characteristics that can make the vehicle detectable by certain sensors operating in a particular spectral region. In the visible through near-infrared spectrum, the detectability of a satellite is a function of the direction and intensity of the solar energy, earth albedo, and/or artificial illumination energy reflected by the external surface of the vehicle. Similarly, in the thermal or far infrared regions of interest in this study, the radiated energy primarily determines the detectability.

Detectability is based on a geometric description of the satellite and a general description of the thermophysical properties of the vehicle surfaces together with the basic orbital parameters and internal heat generation rates. For an accurate representation of infrared signatures, the spectral and directional characterization of the surface reflectance or emittance should be included. The determination of these properties for a selected group of materials and coatings was the primary purpose of this study.

For further discussion of the theory of radiative properties, the reader is directed to the sources listed in the Bibliography.

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II. OPTICAL AND THERMAL RADIATIVE PROPERTIES

In order that presentation of data be as clear as possible, the properties utilized, their corresponding definitions and symbols are summarized here.

Emittance (ϵ)	Ratio of the radiant emission per unit area of the specimen to that emitted by a blackbody radiator at the same temperature.
Reflectance (ρ)	Ratio of reflected radiant flux to incident flux, a function of radiation wavelength and surface temperature.
Absorptance (α)	Ratio of the absorbed radiant flux to the incident flux, a function of radiation wavelength and surface temperature.

The following terminology is used to qualify these basic properties in terms of the wavelength.

Spectral, λ	Function of wavelength usually in a narrow band of wavelengths (also referred to as monochromatic).
Total, T	Ordinarily refers to emittance only. The temperature of the specimen should be specified since the total emittance varies with temperature.
Integrated	Relative to some specified wavelength distribution or specified band.
Solar, s	Having the wavelength distribution of or approximating the sun. When used in conjunction with α the spectral absorptance of the specimen has been integrated over the wavelength distribution of the sun.

In addition, a number of geometric subscripts or qualifiers associated with the incident, reflected or emitted fluxes are also utilized as follows:

Normal, N	Conditions for viewing through an angle θ that is essentially normal to the specimen.

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Angular (directional)	Conditions for viewing at some angle θ.
Hemispherical, H	Conditions for incidence or viewing over a hemispherical region (i.e., 2π steradians).

For analysis of infrared signatures, the angular (directional) and spectral emittance is of primary interest. Detailed emittance data on all of the materials of interest are limited. However, the emittance of a material surface can be related to other optical properties which are more easily obtained or more readily available. Without going into the details of the proof from Kirchoffs law, it follows that for an opaque material in equilibrium with its environment:

$$\epsilon(\lambda, T, \theta) = \alpha(\lambda, T, \theta)$$

$$\epsilon(\lambda, T, \theta) = 1 - \rho(\lambda, T, \theta)$$

In other words if the properties are evaluated at the same temperatures, wavelengths and angles of incidence or viewing, the emittance is equal to the absorptance and the emittance is equal to one minus the reflectance. Thus, under properly controlled conditions, measurement of the angular (directional) spectral reflectance is equivalent to measuring the angular (directional) spectral emittance. The resulting accuracy from this assumption is adequate for most engineering applications and is considered satisfactory for this study.

The values given for total emittance (either normal or hemispherical) for the various materials and coatings in this report are generally defined for some nominal temperature: either at room temperature, at 70°F, or some other specific temperature, depending on the source and conditions under which the data were obtained. Based on the spectral emittance data given for these materials, the total emittance can be computed for any other temperature desired by calculating the blackbody characteristics as given by Planck's law. The actual power emitted or absorbed is obtained by taking the product of the blackbody radiant intensity and the emittance at each wavelength. The total

emittance is then determined by integrating this product over all wavelengths and dividing by the blackbody energy over the same wavelengths.

Many experimental techniques for measuring the thermal radiative properties of materials have been described in the literature and no attempt will be made to discuss the methods or instruments in detail here. It will be noted only that the methods fall into two general categories, radiometric and calorimetric. In calorimetric techniques the radiant flux absorbed or emitted is evaluated in terms of heat lost or gained by the sample. In radiometric techniques, the radiant flux is measured directly or compared with a calibrated reference sample.

Calorimetric methods generally tend to be relatively simple but of lower precision, while radiometric methods require more elaborate equipment and are capable of higher precision but subject to systematic errors that can be difficult to evaluate. Calorimetric methods are used to measure absorptance and emittance (usually the total hemispherical emittance) and are not suitable for direct measurement of reflectance.

Radiometric methods measure the emitted or incidence radiant flux directly as a function of angle from the normal and/or wavelength. Thus, absorptance, spectral and directional reflectance and emittance properties can be determined. In the case of evaluating solar absorptance (α_s), the spectral reflectance is integrated on an energy weighted basis using the solar spectral distribution such as shown in Figures 1(a) and (b) from Refs. 1 and 2, respectively.

When the emittance is the property of interest, measurements are usually taken at near-normal incidence and hence the value of the normal

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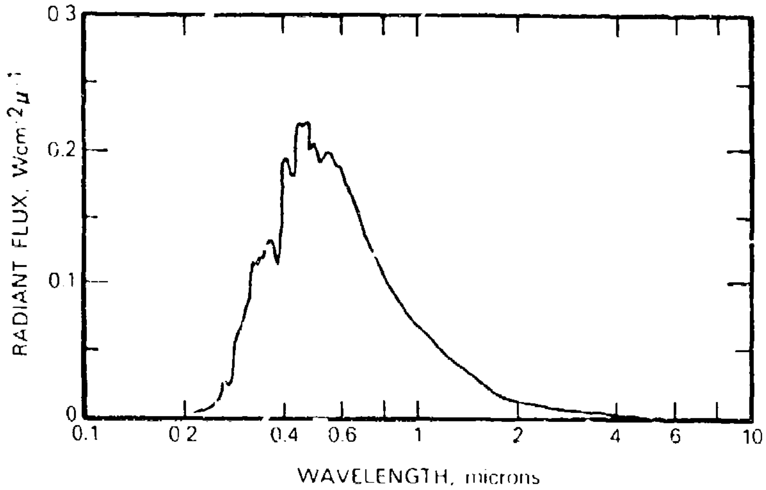
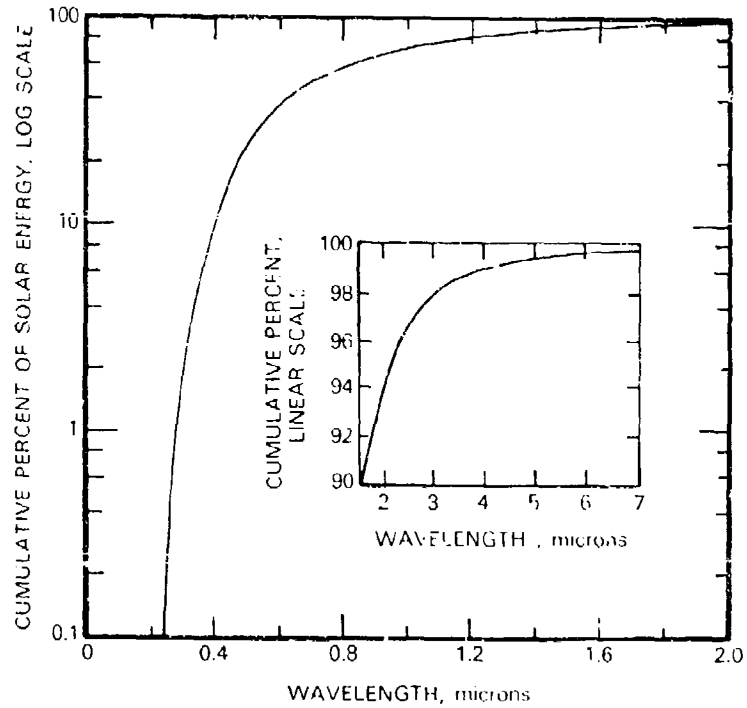
[1] Johnson, F. S., "The Solar Constant," J. of Meteorology, Vol. II, December 1954.

[2] Stark, R., "Thermal Testing of Spacecraft," Report No. TOR-0172(2441-01)-4, The Aerospace Corp., El Segundo, Calif., September 1971.



(a) Spectral irradiance by solar energy (Ref. 1)



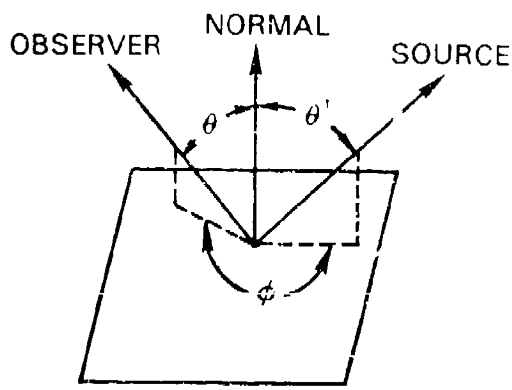
(b) Percent of solar energy contributed by all wavelengths shorter than the indicated wavelengths (Ref. 2)

Figure 1. Solar Spectrum at Zero Air Mass

emittance (ϵ_N) is obtained either on a spectral or total basis. Although the directional emittance can also be obtained, it is not ordinarily measured in the longer (IR) wavelengths.

In these cases the normal emittance (ϵ_N) is used to estimate the hemispherical emittance (ϵ_H) based on ratios of ϵ_N to ϵ_H that have been established for similar materials either on an experimental or analytical basis. Given ϵ_H and ϵ_N, together with various optical constants of the material, directional emittance can then be computed (although quite complex) from electromagnetic theory (Ref. 3). These derivations are quite lengthy and thus are not included in this report. However, a summary of the significant equations are provided in the appendix. The interested reader is directed further to specific texts on radiative heat transfer cited in the Bibliography.

In some applications, a rigorous analytical treatment of the radiative energy interchange between surfaces requires knowledge of the reflectance distribution function which provides the flux reflected in a particular direction as measured by angles θ and ϕ relative to the flux incident from some fixed direction. (See sketch)



Bidirectional Angles for an Area Element

[3] Herring, R. G. and T. F. Smith, "Surface Radiation Properties from Electromagnetic Theory," Int. J. Heat and Mass Transfer, Vol. 11, pp 1567-71, 1968.

This reflectance is termed the bidirectional reflectance. In the case of signatures in the visible and near infrared, the solar energy reflected from an object in space is of primary interest and bidirectional reflectance data is obviously important.

In contrast, in the case of the thermal or far-infrared signatures of interest for this study, self-emission of external surfaces of objects provides the predominate source of energy and bidirectional reflectance data is of less significance. Also, as the wavelength increases, the magnitude of the surface roughness dimensions become smaller relative to the wavelength dimensions and the bidirectional reflectance effect is diminished.

Another factor is the complexity and quantity of data required for application of bidirectional reflectance. If the bidirectional reflectance of a surface is mapped at reasonably close-spaced angular increments, a rather large set of numbers is required. For example, in a case where polar increments are set at 10° (θ and θ') and the azimuth increments (ϕ) are set at 20°, there are 1458 (i.e., $9 \times 9 \times 18$) individual reflectances required for just one wavelength. As the wavelength regions or bands of interest are increased, the number of data points for each surface of interest becomes substantial.

Therefore, due to these factors and the relatively large number of materials involved, the inclusion of bidirectional reflectance data was considered to be beyond the scope of this preliminary study.

III. OPTICAL AND THERMAL RADIATIVE PROPERTIES DATA

Ideally, thermal control surfaces can be divided into four basic classes: solar absorbers, solar reflectors, flat absorbers and flat reflectors, as illustrated in Figure 2 from Ref. 4. The solar absorbers are primarily polished metals which exhibit a high α_s and a relatively low α in the longer IR wavelengths. Flat absorbers such as black paints generally exhibit a high α over both the solar and IR wavelengths. This characteristic is also typical of solar cells.

Flat reflectors which exhibit a relatively flat but moderate α over the wavelength range through the IR are typical of aluminum paints. Solar reflectors with a low α_s and a high ϵ in the IR region are typical of specifically developed white paints and second surface mirrors which are also referred to as optical solar reflectors (OSR's). The OSR's consist of vapor deposited silver, aluminum or gold overlaid with clear transparent layers of fused silica, Teflon, Mylar, etc. The transparent layer allows transmission of solar energy to the metal film where a large percentage of it is reflected. This transparent layer is, however, relatively opaque in the IR wavelengths, and therefore, exhibits a high emittance. Thus, the OSR composite reflects most of the solar energy while at the same time providing an efficient radiator to maximize heat rejection capability.

In a space environment, the white paints exhibit the least stability (i.e., they exhibit an increase in α_s) while the second surface mirrors tend to be the most stable. (Quantitative data are presented in Paragraphs III-B and III-D.) The significance of this is that with white paint the equilibrium temperature of a spacecraft surface increases with time on orbit. A variation of the conventional second surface mirror involves anodized aluminum,

[4] Broadway, N. J., "Radiation Effects Handbook, Section 2, Thermal Control Coatings," NASA-CR-1786. Prepared by Battelle Memorial Institute, Columbus, Ohio, June 1971.

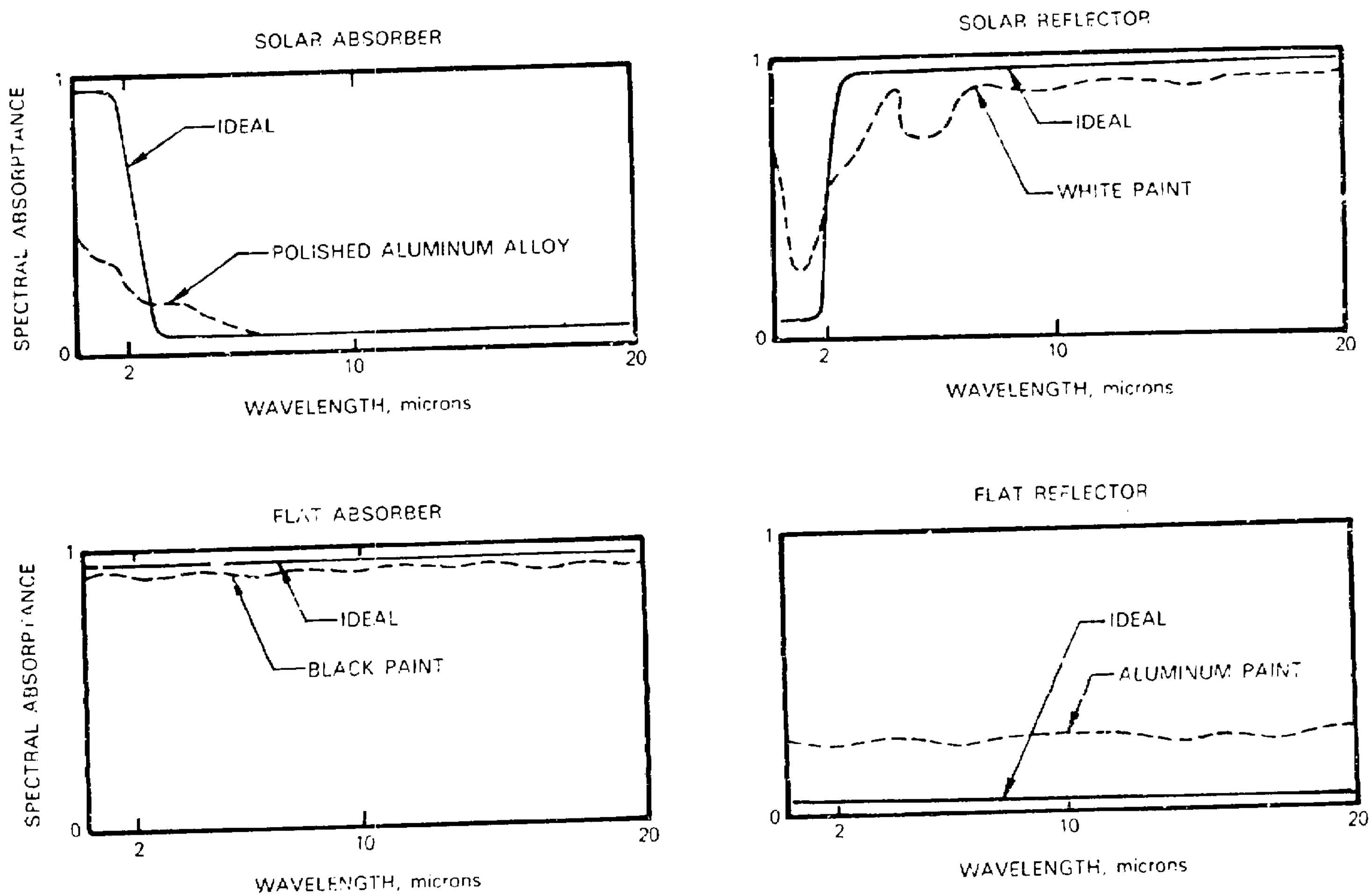


Figure 2. Ideal Representation of Four Basic Surfaces and Production Materials (Ref. 4)

wherein a transparent aluminum oxide film is chemically formed on a bright polished aluminum substrate. The stability of this surface tends to be somewhat better than most of the white paints (quantitative data are presented in Paragraph III-C).

For the purpose of presentation, data are grouped into the following material categories: metallic surfaces, coatings of white, black, or aluminum pigments, anodized aluminum, second surface mirrors and solar cells.

A. METALLIC SURFACES

The normal (i.e., 90 degrees from the surface) spectral reflectance of various aluminum alloy 6061 specimens is shown in Figure 3, based on Ref. 5. The strong influence of the surface characteristics of the specimens on reflectance is clearly visible. A second source of data (Ref. 6) is presented in Figure 4 for 6061 aluminum plate with a surface condition defined as unpolished as received from the supplier. For this specimen, $\alpha_s = 0.37$ and $\epsilon_H = 0.042$ at room temperature. These will be the assumed characteristics for 6061-Al unpolished surfaces.

Normal spectral reflectance for two commonly used titanium alloys (6Al-4V and 5Al-2.5 Sn) are presented in Figure 5. Data from Ref. 5 for 6Al-4V did not specify wavelengths beyond four microns, thus the curves shown for this alloy for wavelengths beyond four microns has been estimated to be the same as that shown for the 5Al-2.5Sn alloy since the difference in reflectance values between specimens of titanium at the longer wavelengths tend to be relatively small. The unpolished 6Al-4V specimen is selected as the baseline titanium alloy with properties of $\alpha_s = 0.57$, $\epsilon_H = 0.18$ from

[5] Touloukian, Y. S., et al, "Thermophysical Properties of Matter, Thermal Radiative Properties," Thermophysical Properties Research Center, Purdue University, 1972.

[6] Thermophysical Properties Measurement, Unpublished Data, TRW, Redondo Beach, California.

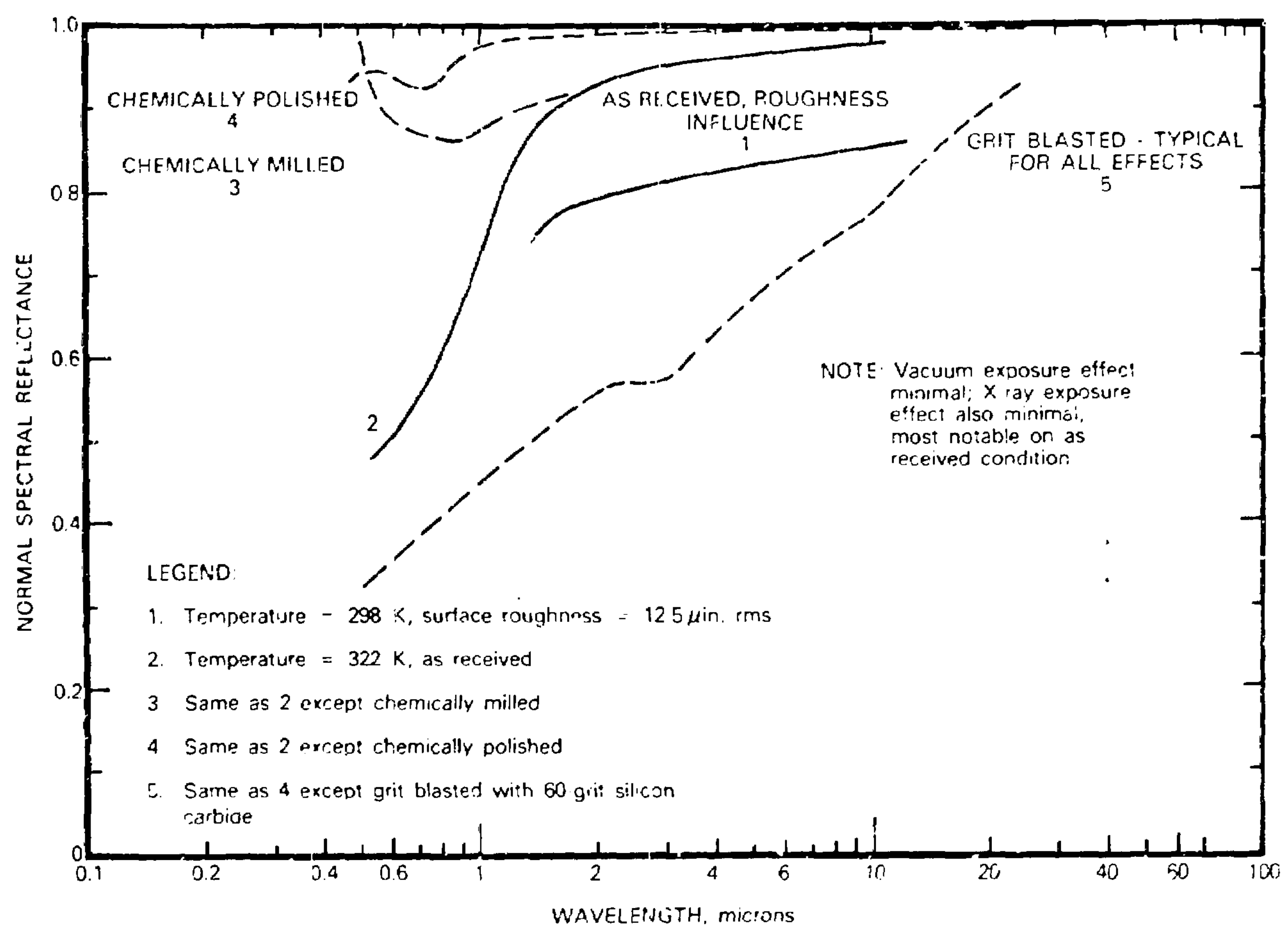


Figure 3. Normal Spectral Reflectance of Various Aluminum Alloy 6061 Specimens (Ref. 5)

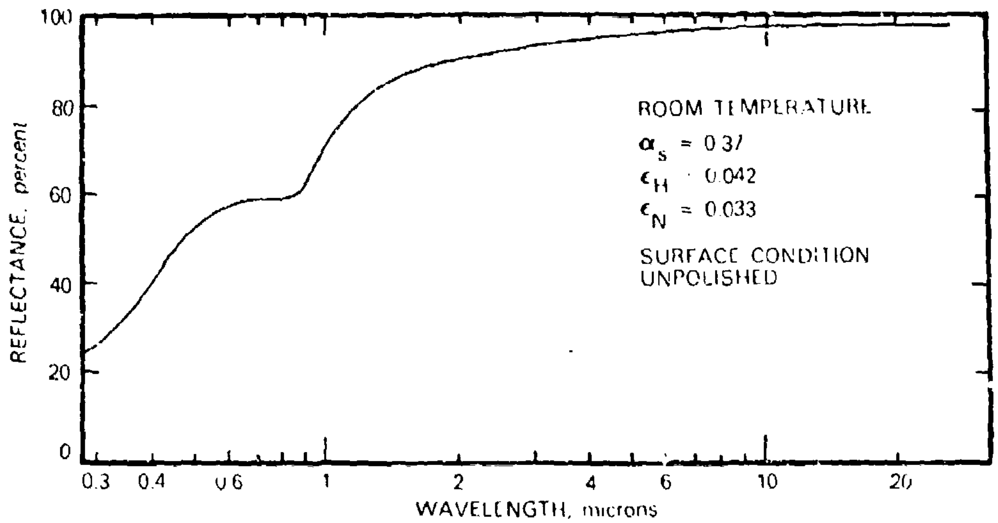


Figure 4. Normal Spectral Reflectance for Aluminum Alloy 6061

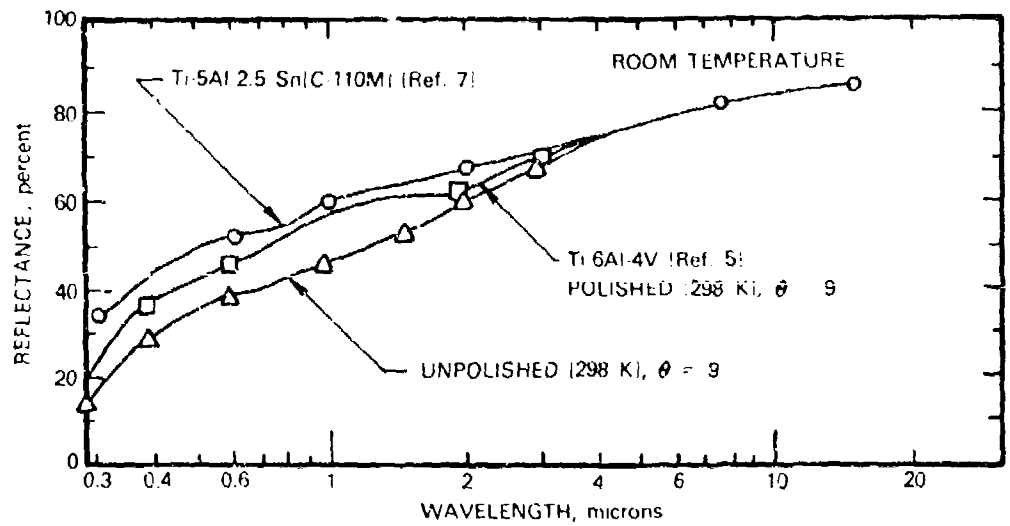


Figure 5. Normal Spectral Reflectance for Two Titanium Alloys

Ref. 5, and is assumed to have the same reflectance properties beyond four microns as that shown for the 5Al-2.5Sn specimen, from Ref. 7.

No angular (directional) reflectance or emittance data were available for either of the specific aluminum or titanium alloys. However, representative data for several metals are presented in Figure 6 (Ref. 8). In general, all metals follow the same form as shown in Figure 6; i.e., ϵ remains quite uniform at angles less than 40° and then increases sharply at larger angular inclinations. Although the experimental data shown were not carried out to 90°, the directional emittance would approach zero. In general, the percentage increase in ϵ with increasing angle is more pronounced when the value of ϵ is low. This is opposite to that for nonconductors (e.g., glass, paints, plastics, etc.), wherein the emittance normally is quite uniform up to about 50° and then decreases with large angles of θ away from the normal.

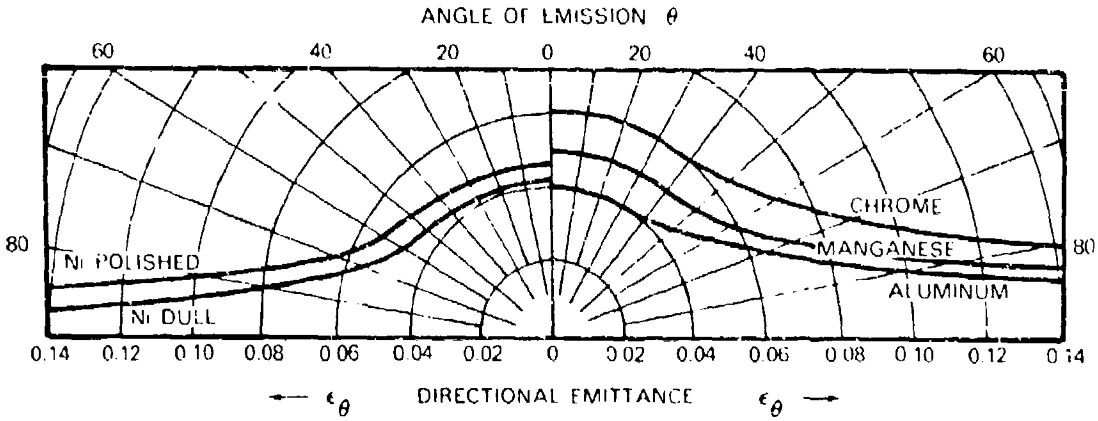


Figure 6. Directional Emittance Variation for Several Metals (Ref. 8)

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7 Gubareff, G. G., "Thermal Radiation Properties Survey," 2nd Ed., Honeywell Research Center, Minneapolis - Honeywell Regulator Co., Minneapolis, Minn., 1960.

8 Schmidt, E. and Eckert, E., "Uber die Richtungsverteilung der Warme - strahlung," Forsch. Gebeite Ingenieorwesen, Vol. 6, 1935.

Based on Figure 6, the directional emittance for aluminum at angles less than 40° corresponds reasonably well with the ϵ_H and ϵ_N values defined for the 6061 specimen in Figure 4. Thus, as an approximation, it can be assumed that the directional emittance variation given for Al on Figure 6 can be applied to the normal spectral emittance values given on Figure 4. On this basis, the ratio of $\epsilon_\theta/\epsilon_N$ and the corresponding value of ϵ_θ can be estimated as shown in Table 1.

For metal surfaces, the ratio of ϵ_H/ϵ_N is generally greater than 1.0. Although this ratio can be calculated from electromagnetic theory, an empirical relation is given in Figure 7 based on measured data as a function of the normal emittance. Although no directional emittance data were found for the specific titanium alloy of interest (i.e., 6Al-4V), directional spectral data

Table 1. Calculated Directional Emittance for 6061 Aluminum

Angle from Normal (θ)	ϵ_θ (from Figure 6)	$\epsilon_\theta/\epsilon_N$ (from Figure 6)	ϵ_θ for 6061 Al (ϵ_N = 0.033)*
0	0.04 (ϵ_N)	1.0	0.033
20	0.04	1.0	0.033
40	0.041	1.02	0.034
50	0.044	1.10	0.036
60	0.050	1.25	0.041
70	0.065	1.62	0.054
80	0.105	2.62	0.086
90	0.00	0.00	0.00

*Based on ϵ_H/ϵ_N = 1.28 for metallic surfaces and ϵ_H = 0.042.

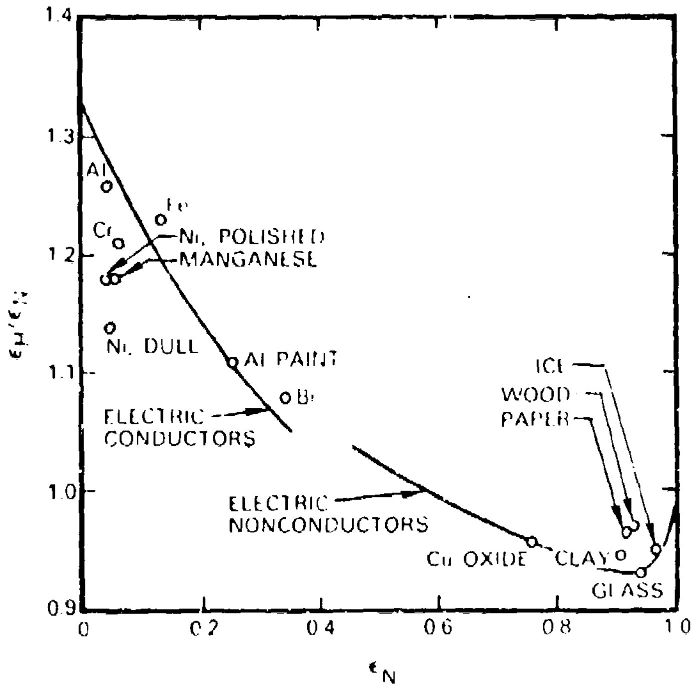

Figure 7. Ratio of Hemispherical to Norm. . Emissivity (Ref. 7)

for pure titanium are illustrated in Figure 8 (Ref. 9). At very short wavelengths it can be seen that the directional spectral emissivity actually decreases with increasing angle θ which is somewhat contrary to the normal behavior of metals as predicted by electromagnetic theory. However, for the region of interest, i.e., the longer IR wavelengths, the emissivity does increase with increasing θ. The directional emittance for Ti-6Al-4V can be estimated utilizing the combined data presented in Figures 5, 7, and 8.

[9] Edwards, D. K., and Ivan Catton, "Radiation Characteristics of Rough and Oxidized Metals," Advances in Thermophysical Propertie at Extreme Temperature and Pressures, ASME, 1965, pp. 189-199.

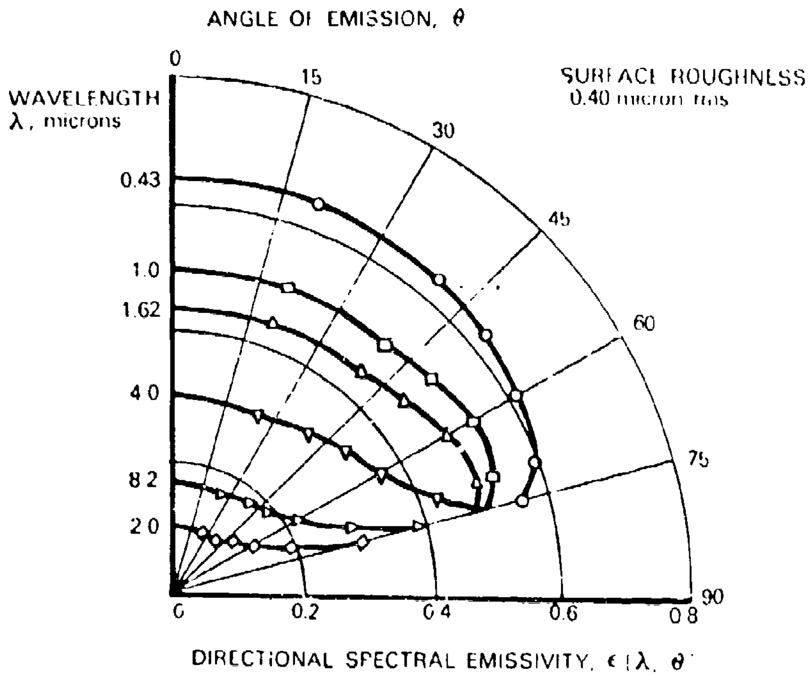

Figure 8. Effect of Wavelength on Directional Emissivity of Pure Titanium (Ref. 9)

Beryllium is used for a wide variety of purposes including heat shields, optical mirrors and in nuclear reactor technology as a neutron reflector surface. Spectral reflectance data from Ref. 5 are presented in Figure 9 for an extruded sample of beryllium. The total normal emittance (ϵ_N) for this sample is computed as 0.14 at 500°F. The corresponding value for ϵ_H is estimated as 0.17 utilizing Figure 7 as a basis. The α_s for beryllium is assumed to be 0.70, from Ref. 10.

[10] Gaumer, R. E. and L. A. McKeder, "Thermal Radiative Control Surfaces for Spacecraft," LMSC-704014, Lockheed Missiles and Space Co., March 1961.

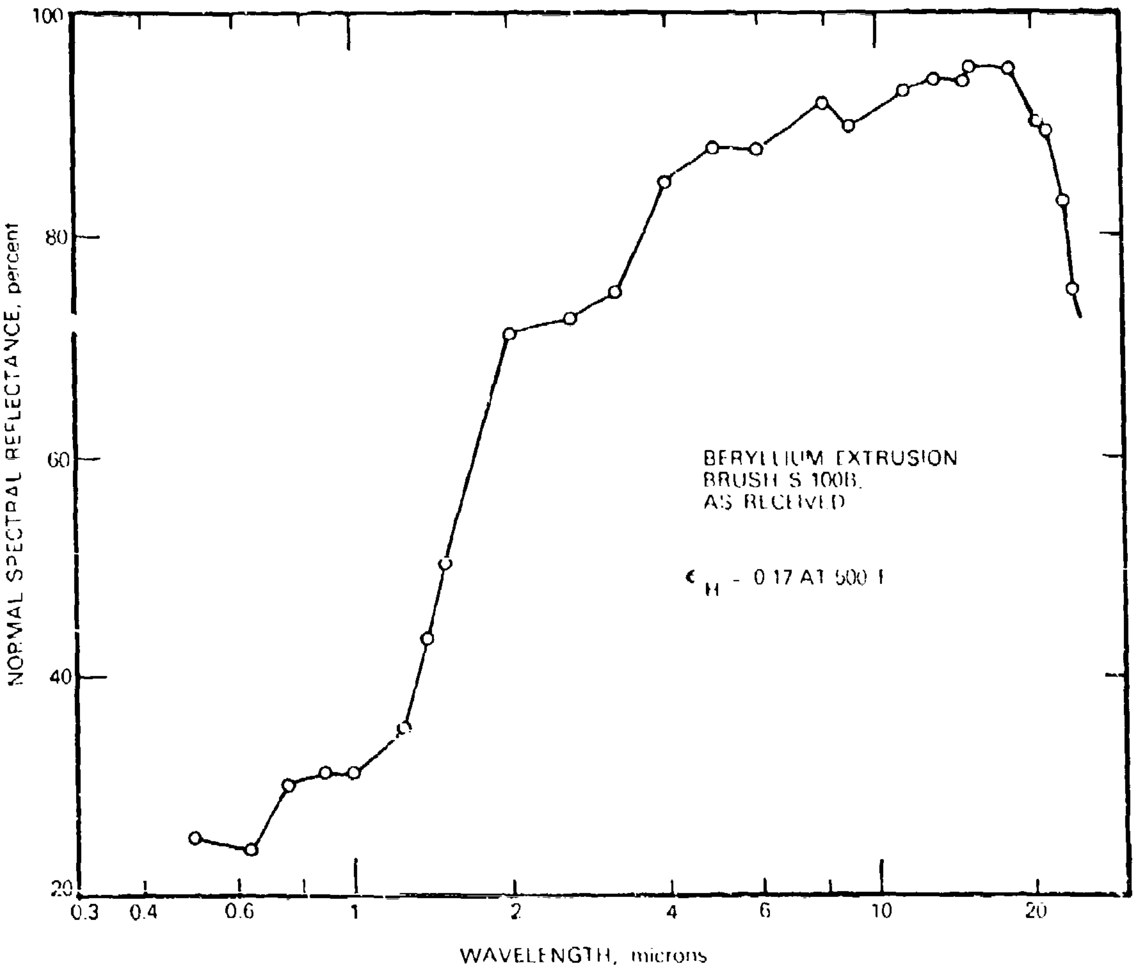

Figure 9. Normal Spectral Reflectance of Beryllium (Ref. 5)

B. COATINGS

1. SOLAR REFLECTORS - WHITE PAINTS

A number of white paints have been developed which are utilized as solar reflectors. A listing of some of the more common ones are presented in Table 2. All of these coatings, however, are degraded to different degrees by the space environment. The primary damaging factors include UV radiation, electron and proton bombardment and nuclear radiation. The change in solar absorptance (α_s) of three common zinc oxide pigmented coatings, i.e., Z-93, S-13 and S-13G, as a result of exposure to various environments are summarized in Figure 10. The accelerated degradation effect of the added particle bombardment associated with high altitude/deep space environments is indicated. The change in α_s for a titanium dioxide base paint (white Thermatrol, Refs. 11 and 12) is shown in Figure 11. The higher degradation rate for the synchronous orbital altitude associated with the ATS-1 is also illustrated here.

Of the white paints illustrated, Z-93 is considered to be the most stable. The major problems with this coating are the difficulty of application, the more complex curing process and ease of soiling during preflight conditions. Therefore, the use of the S-13, S-13G or the titanium dioxide base paint, Dow Corning (DC-92-007) is preferable. Spectral reflectance data are presented for DC-92-007 and S-13C on Figure 12 (Ref. 6) and Figures 13 and 14, from Ref. 13. These data as noted are measured at angles at or near normal. Reflectance data for PV-100 as utilized on the Nimbus and ERTS programs are shown in Figure 15 from Ref. 14. However, a significant change in the

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[11] Hultquist, A. E., et al, "Advanced Thermal Control Materials Development," LMSC-A967871, Lockheed Missiles and Space Co., May 1970.

[12] Personal Communication, Aerojet Electro-Systems Co., Azusa, Calif., 13 July 1973.

[13] Bair, M., et al,"Optical Properties of Satellite Materials,"(Draft Copy), Document No. 194100-6-F, Infrared and Optics Division, Environmental Research Institute of Michigan, Ann Arbor, Mich., July 1973.

[14] Personal communication, A. Eagles, General Electric Valley Forge Space Center, Philadelphia, Pa., 2 Oct 1974 (ERTS-I Surface Coating Optical Properties Test Data).

Table 2 White Paints Suitable for Spacecraft Thermal Control

Designation	Characteristic Formulation	Mfg. or Developer	Typical Spacecraft Applications	Approximate Thermal Properties		Ref.
				$(\alpha_s)^*$	$(\epsilon_H)^*$	
Thermatrol (DC 92-007)	Titanium Dioxide (TiO_2) Pigment Silicone Binder	Lockheed Dow Corning	Lunar Orbiter, [illegible]	0.19	0.82	4
S-13	Zinc Oxide (ZnO) RTV 602 Binder	Illinois Inst. of Tech. Res. Inst.	ATS 1, OSO I	0.21	0.88	4
S-13G	Zinc Oxide/ Potassium Silicate with RTV 602 Binder	Illinois Inst. of Tech. Res. Inst.	Lunar Orbiter II, III, IV, Mariner V, [illegible]	0.19	0.88	15
Z-93	Zinc Oxide/ Potassium Silicate Binder	Illinois Inst. of Tech. Res. Inst.	OSO III, Mariner IV, Apollo SM Radiators	0.18	0.88	4
PV-100	Titanium Dioxide/ Silicone Alkyd Binder	Vita Var GE	Nimbus, ERTS A	0.[illegible]	0.82	14
Kemacryl	Titanium Dioxide/ Acrylic Binder	Sherwin-Williams	--	0.24	0.86	16
Skyspar	Titanium Dioxide/ Epoxy Binder	Andrew Brown Co.	--	0.22	0.91	16

*At room temperature

[15] Carroll, W. F., "Mariner V Temperature Control Reference Design, Test and Performance," JPL, Pasadena, Calif. Paper presented at AIAA 3rd Thermophysics Conference, L. A., Calif., June 24-26, 1968.

[16] Rittenhouse, J. B., et al, "Space Materials Handbook," NASA SP-3025, Supplement 1, 1966.

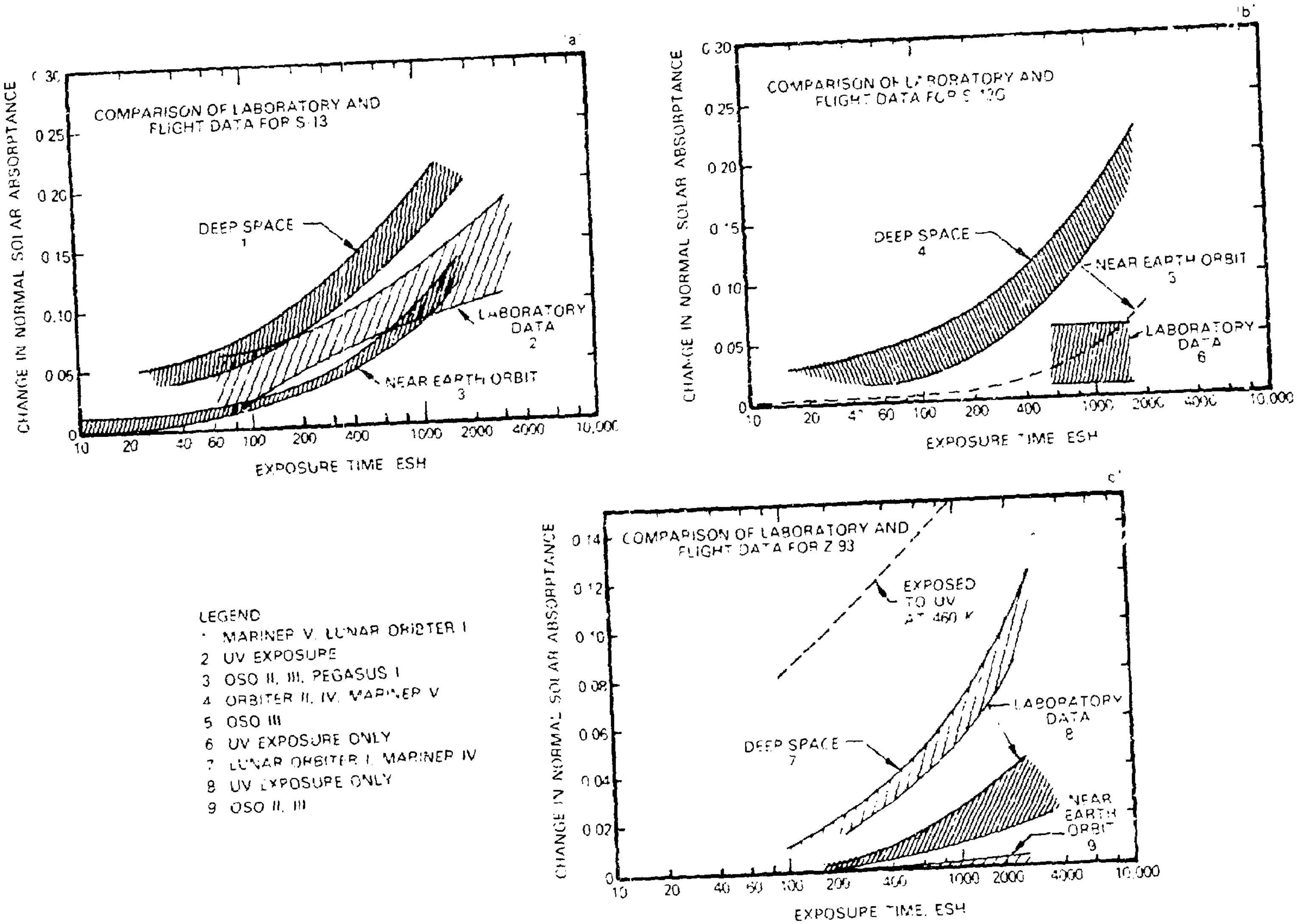

Figure 10. Change in Normal Solar Absorptance of Zinc Oxide Pigmented Coatings (Ref. 5)

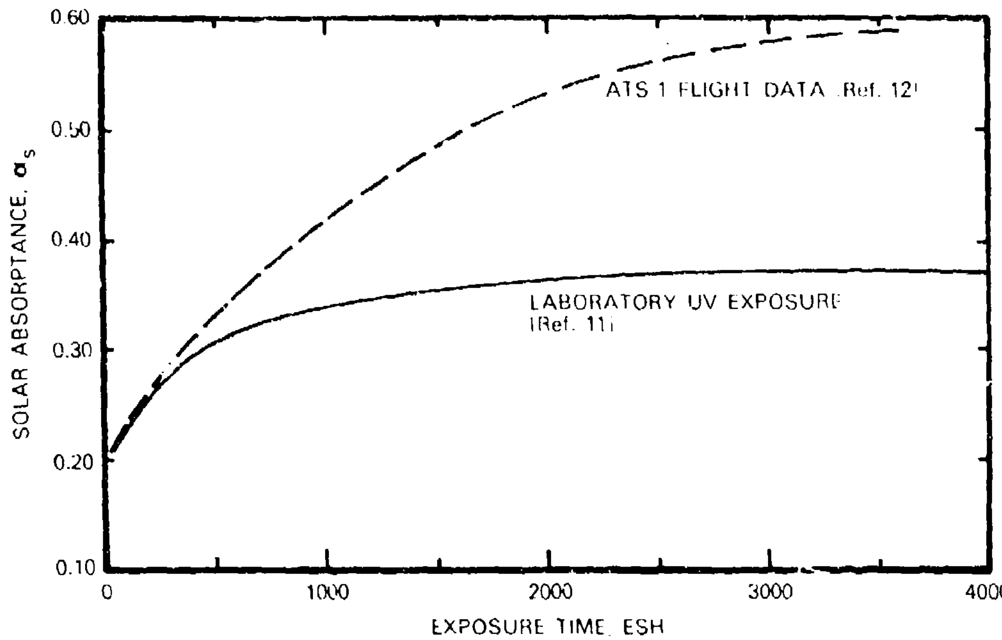

Figure 11. Change in Solar Absorptance of White Thermatrol Paint

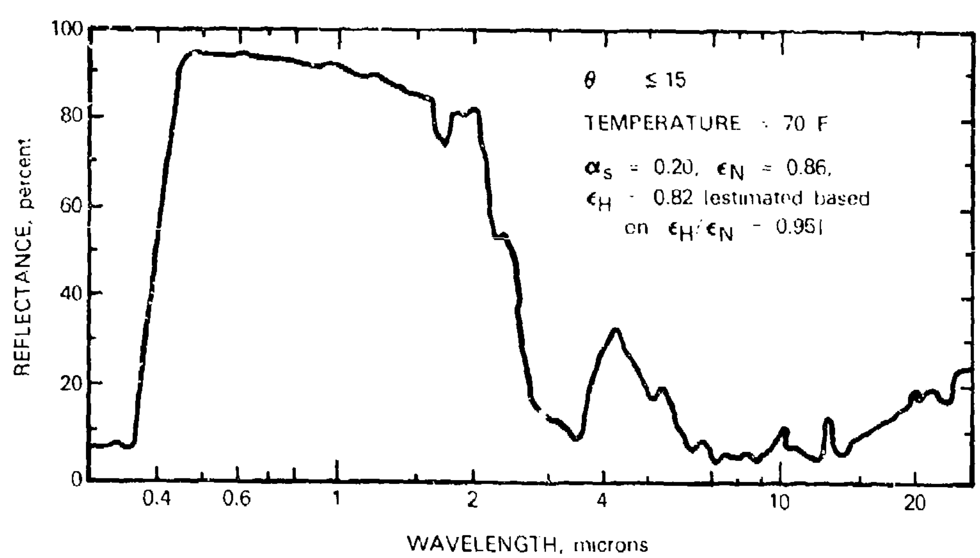

Figure 12. Spectral Reflectance for DC 92-007 White Paint

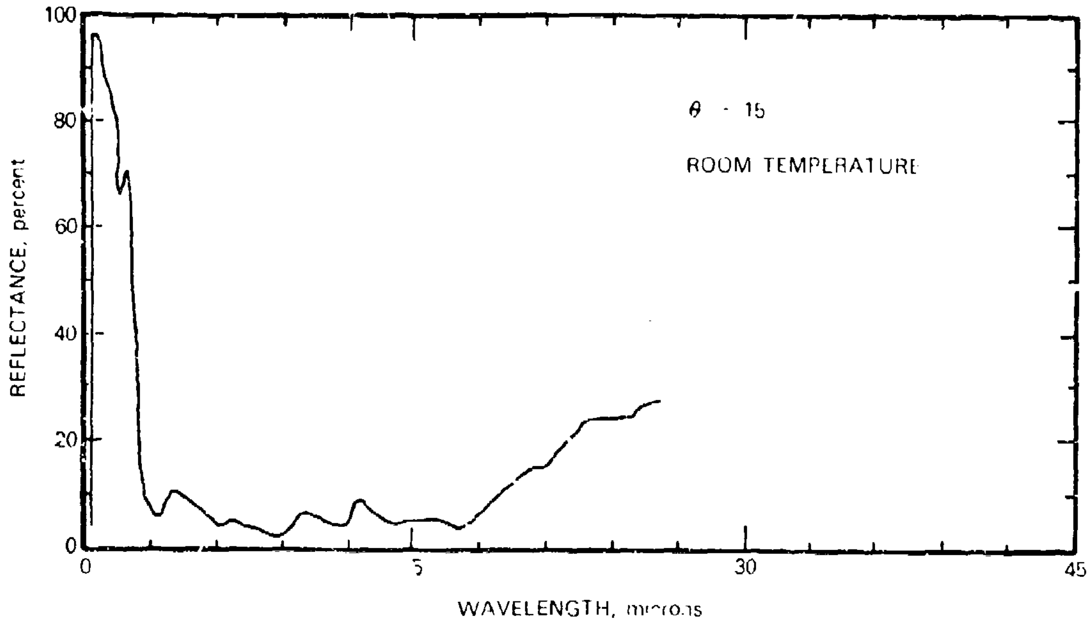

Figure 13. Normal Spectral Reflectance for S-13G White Paint (Ref. 13)

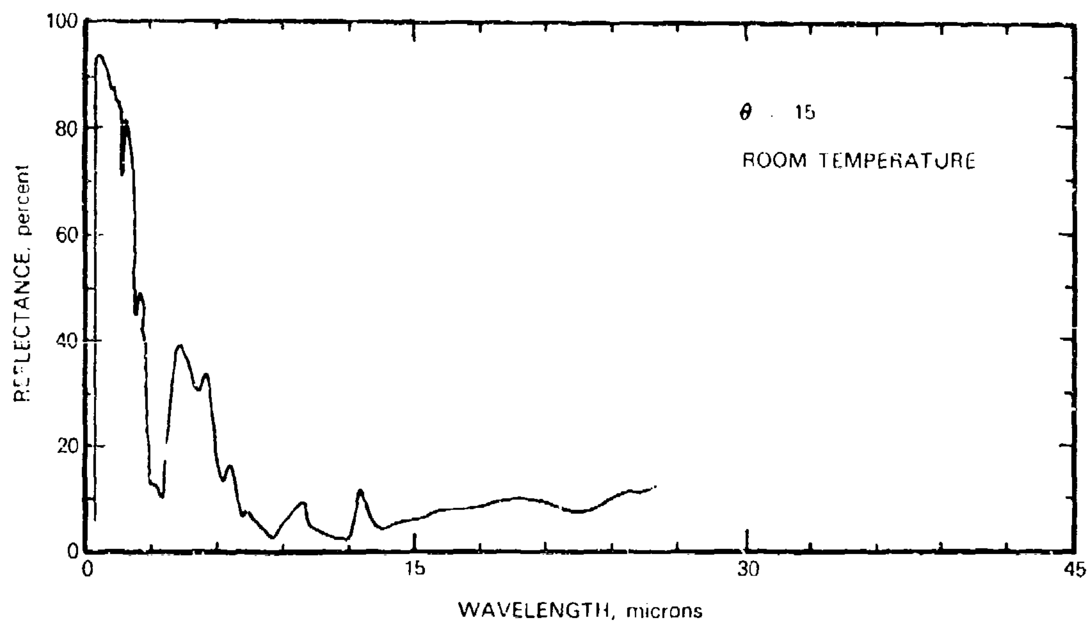

Figure 14. Normal Spectral Reflectance for White Thermatrol Paint (Ref. 13)

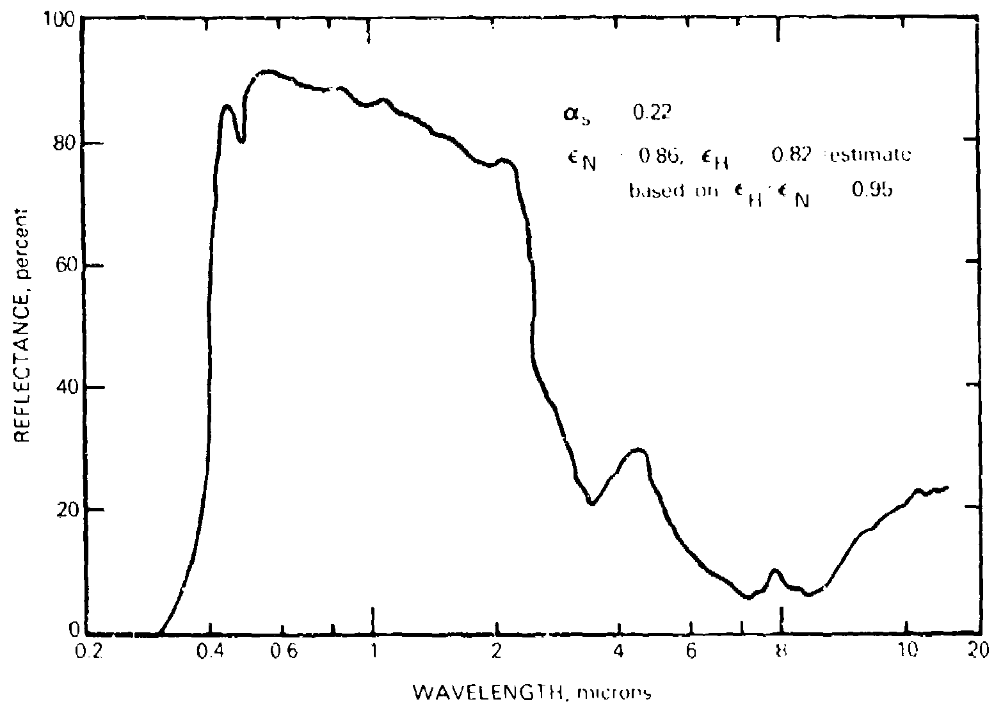

Figure 15. Spectral Reflectance of PV-100 White Paint (Ref. 14)

directional reflectance would not be expected for these coatings at angles less than about 50° since most nonconductors exhibit characteristics as illustrated in Figure 16.

Inspection of results obtained by Schmidt and Eckert (Ref. 8) in Figure 16 shows that the directional emittance remains essentially uniform for angles between 0° and 50°; then drops off quite rapidly to zero. This relationship is, in general, in accord with that predicted by electromagnetic theory. The relationship between ϵ_H and ϵ_N is relatively complex, depending on the wavelength, refractive index and dielectric constant. In general, however, the ratio ϵ_H/ϵ_N for nonconductors falls between 0.93 and 1.0 as indicated in Figure 7. For analysis purposes, the directional emittance of any of these white paints can be assumed to follow the relationships typical of those given in Figure 16 for nonconductors.

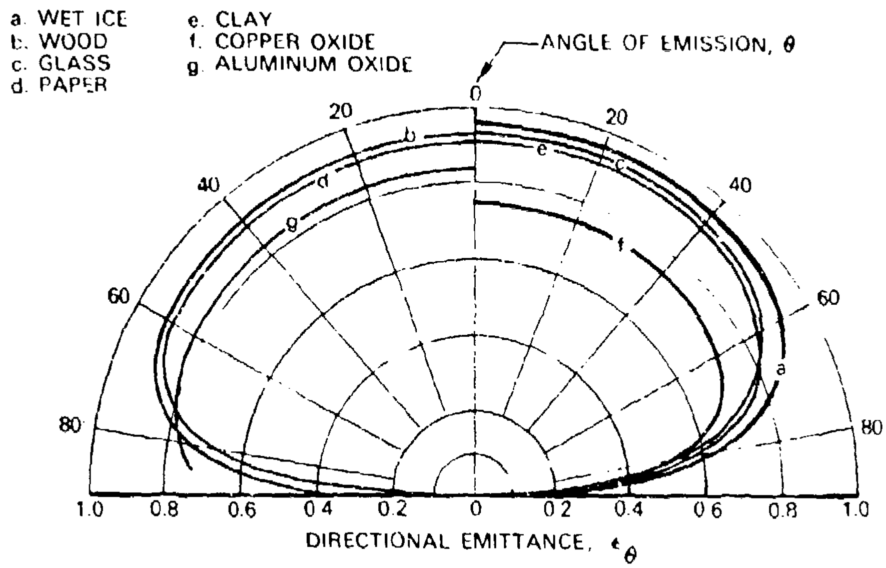

Figure 16. Directional Emittance Data for Several Electrical Nonconductors (Ref. 8)

2. FLAT REFLECTORS - ALUMINUM PAINTS

Materials which exhibit relatively flat wavelength characteristics are typically referred to as flat reflectors. These properties are characterized by aluminum paints.

Normal emittance characteristics of GE-D4D aluminum paint which is extensively used on the Nimbus and ERTS vehicles are presented in Figure 17. These curves were plotted from raw laboratory data (Ref. 14) which yields properties of $\alpha_s = 0.28$, $\epsilon_N = 0.27$ and $\epsilon_H = 0.28$ (estimated) at room temperature.

The normal spectral reflectance of a second aluminum paint is shown in Figure 18 based on Ref. 6 before and after UV exposure. The initial properties of this aluminum paint (Rinshed-Mason) were computed as $\alpha_s = 0.26$, $\epsilon_H = 0.22$. After 2000 hours of laboratory UV exposure, α_s degraded to 0.32, while ϵ_H at room temperature is essentially unchanged.

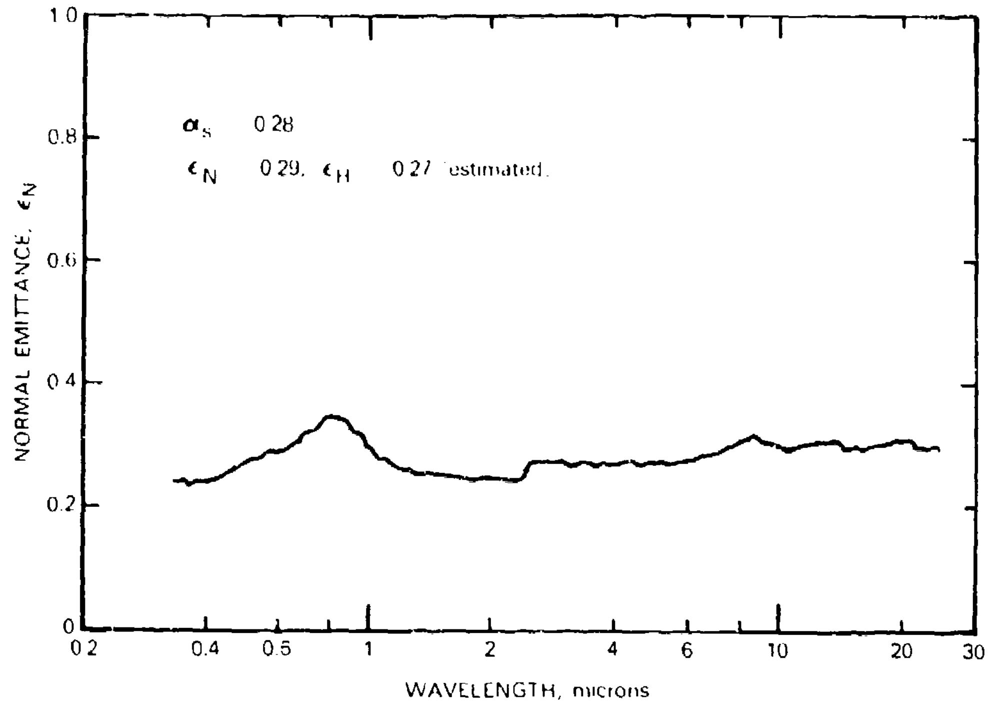

Figure 17. Normal Spectral Emittance of GE D4D Aluminum Paint (Ref. 14)

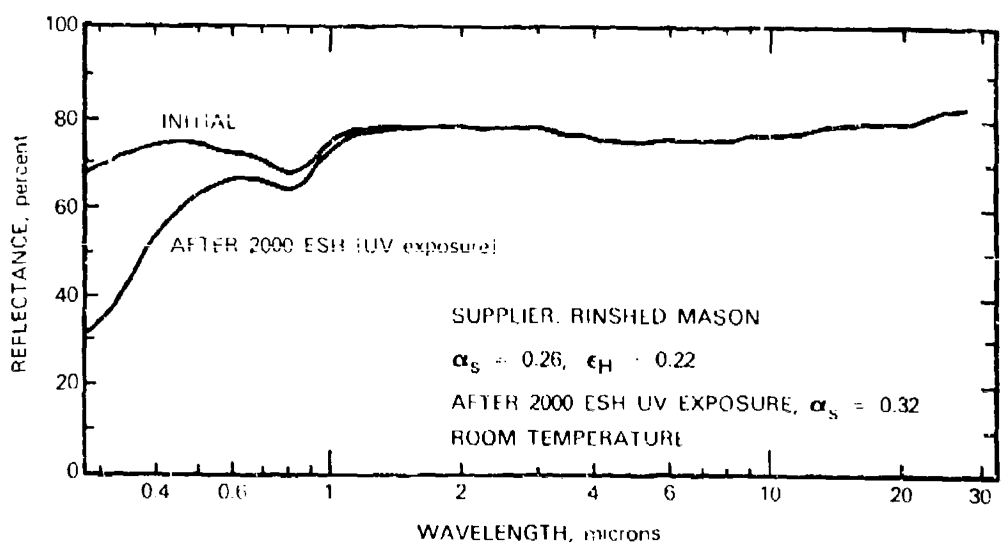

Figure 18. Normal Spectral Reflectance for TRW Aluminum Paint (Ref. 6)

3. FLAT ABSORBERS

a. Black Paints

Representative coatings used as flat absorbers and their thermal properties are summarized in Table 3. In general, these classes of coatings have been shown to be generally stable in the space environment. Directional emittance for 3M Black Velvet paint is illustrated in Figure 19. The experimental data shows that the directional emittance is essentially uniform for angles up to 45° from the normal. At greater angles, the emittance decreases quite rapidly. No data are shown for angles greater than 80°, however, the emittance would be expected to decrease sharply to zero, typical of the curves presented on Figure 16.

Table 3. Representative Black Paints Used for Spacecraft Thermal Control

Designation	Developer or Manufacturer	Solar Absorptance (α_s)	Hemispherical Emittance (ϵ_H)*	Ref.
Chemglaze, Z-306	Hughson Chemical	0.95	0.88	17
Black Velvet (401)	3M	0.95	0.92	18
Black Kemacryl Lacquer (M49RC-12)	Sherwin-Williams	0.93	0.88	4
Black Silicone Paint (517-B-2)	W. P. Fuller	0.89	0.88	4
Cat-a-lac flat black	Finch Paint & Chemical Co.	0.85	0.90	18

*At room temperature

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[17] Personal communication, R. Wallace, Lockheed Missiles and Space Co., Sunnyvale, Calif. 10 Oct 1974.

[18] Personal communication, G. Borson, Aerospace Corp., Materials Science Laboratory, 5 Sept 1974.

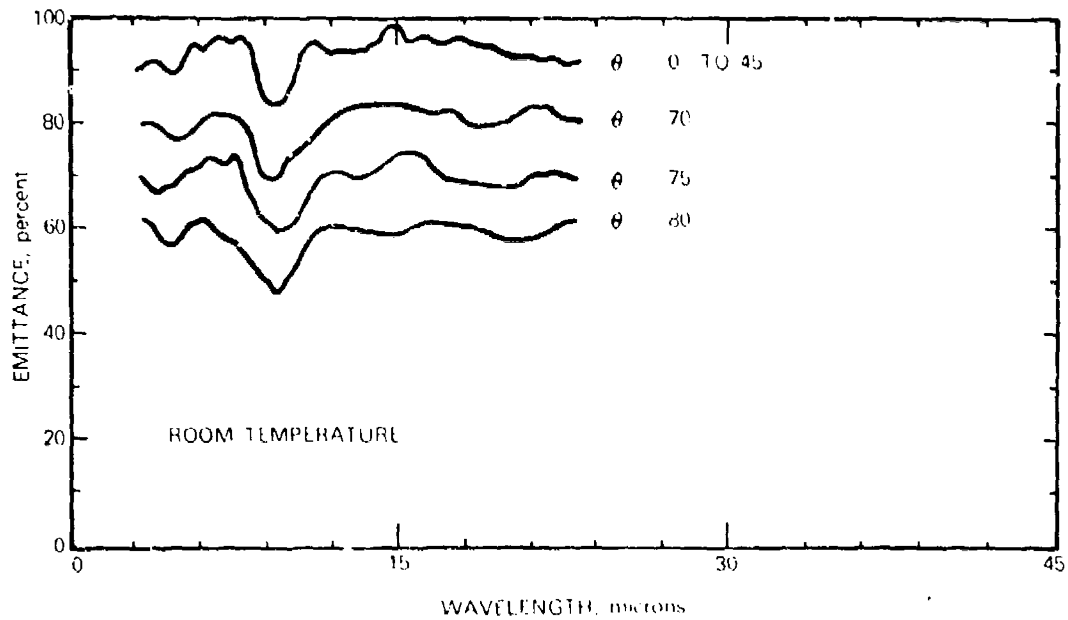

Figure 19. Directional Spectral Emittance of 3M Black Velvet - 401 Paint (Ref. 13)

b. Black Anodized Aluminum

Anodized aluminum blackened by the use of commercially available dyes has been produced and tested for use as solar absorbers (Ref. 19). Tests conducted therein have indicated that these surfaces experience only negligible changes in thermal radiation characteristics when exposed to simulated space environment. Because the black paints typical of those identified in Table 3 are generally limited to temperatures on the order of 400°F, a black anodized aluminum surface is ideal where a high temperature surface with a high emittance and an aluminum substrate are required such as in the case of

[19] Wade, W. R. and D. J. Progra, "Effects of Simulated Space Environment on Thermal Radiation Properties of Selected Black Coatings," NASA TN-D-4116, September 1967.

a nuclear reactor radiator. In addition, the organic-based black paints tend to deteriorate more rapidly when exposed to high intensity radiation in close proximity to a nuclear reactor.

For this type of application, anodized aluminum blackened with an inorganic dye, CoS (cobalt sulfide) has been selected as a logical representative surface. The spectral reflectance for a black (CoS dyed) anodized aluminum surface is illustrated in Figures 20 and 21 both prior and after exposure to a simulated space environment. The environment is specified on the subject figures. The sample used in these tests was 0.125-inch thick commercially pure aluminum 1100 sheet anodized under the following conditions:

Electrolyte	15% sulfuric acid
Current Density	0.1775 amperes/cm^2
Temperature	305°K
Time	120 minutes maximum

To produce the black coating, the pores formed on the aluminum surface by the anodizing process are impregnated by the CoS dye. The initial surface properties prior to the radiation exposure were $\alpha_s = 0.957$ and $\epsilon_N = 0.93$. The properties changed only slightly after exposure. The thermal emittance was obtained utilizing a heated cavity reflectometer (with the sample at approximately 300°K) which yields the normal emittance (ϵ_N). The value of ϵ_H is estimated as 0.87 utilizing Figure 7.

C. CLEAR ANODIZED ALUMINUM

Bright polished aluminum surfaces which have been anodized provide a basic solar reflector material which is relatively stable in the space environment. Aluminum is an excellent reflecting material for radiation in all parts of the spectrum, while the oxide film produced in the anodizing process is transparent in the visible region and relatively opaque in the IR region. The normal emittance of this coating is a direct function of the aluminum

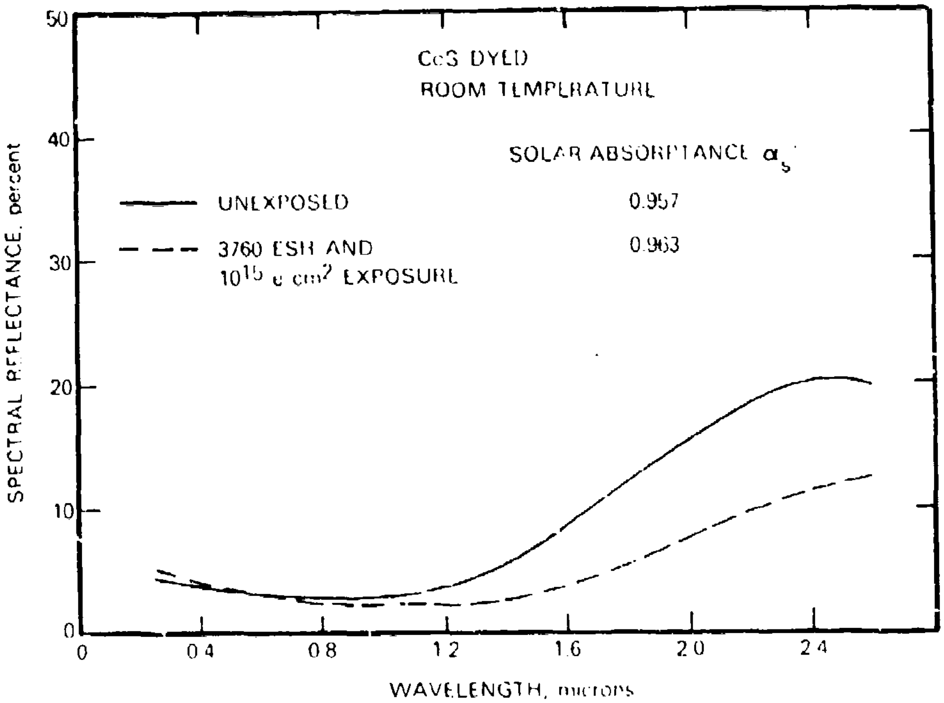

Figure 20. Solar Absorptance of Black Anodized Aluminum (Ref. 19)

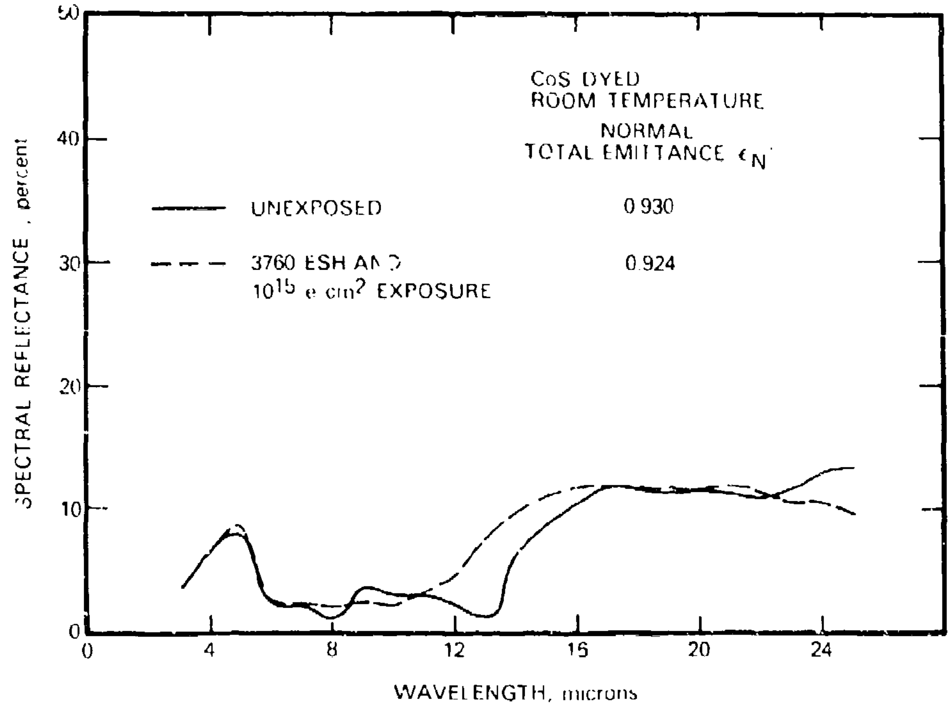

Figure 21. Spectral Reflectance and Total Normal Emittance of Black Anodized Aluminum (Ref. 19)

oxide layer thickness as illustrated in Figure 22. The effect of the oxide layer thickness and temperature on the hemispherical emittance and solar absorptance is illustrated in Figure 23. The coating is relatively stable but does undergo an increase in solar absorptance which is caused primarily by UV exposure. Laboratory and flight data suggest that there is a significant variability in the degradation characteristics from batch to batch even when an identical process is utilized.

Typical changes in α_s, based on Orbiting Astronomical Observatory (OAO) and Orbiting Solar Observatory (OSO) flight data, are shown in Figure 24, based on Ref. 20. The OAO panels consisted of 1199 aluminum substrate with the aluminum oxide layer estimated at 0.26 mils with an initial $\alpha_s = 0.16$, $\epsilon_H = 0.76$. The thickness of the OSO-II oxide layer is undefined.

The normal spectral reflectance of anodized aluminum as a function of the Al_2O_3 layer thickness is shown in Figure 25, from data in Ref. 21.

D. OPTICAL SOLAR REFLECTORS (SECOND SURFACE MIRRORS)

Vacuum deposited films of silver or aluminum covered with a transparent layer of sufficient thickness to achieve the desired high emittance provide an ideal thermal control surface commonly referred to as OSR's. These surfaces have shown excellent stability in both near earth and synchronous altitude orbital flights.

A typical OSR consists of a film of vapor deposited silver (~1000 angstroms) on a 6 mil fused silica facesheet with an overcoating of vapor deposited inconel metal which protects the silver from corrosion or damage

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[20] Fine, H., An Insight into the Features of the OAO Thermal Design, ASME 73-ENAs-46, 20 Aug 1973.

[21] Weaver, J. H., "Bright Anodized Coatings for Temperature Control of Space Vehicles," Plating, 51 (19), 1165-1172, December 1965.

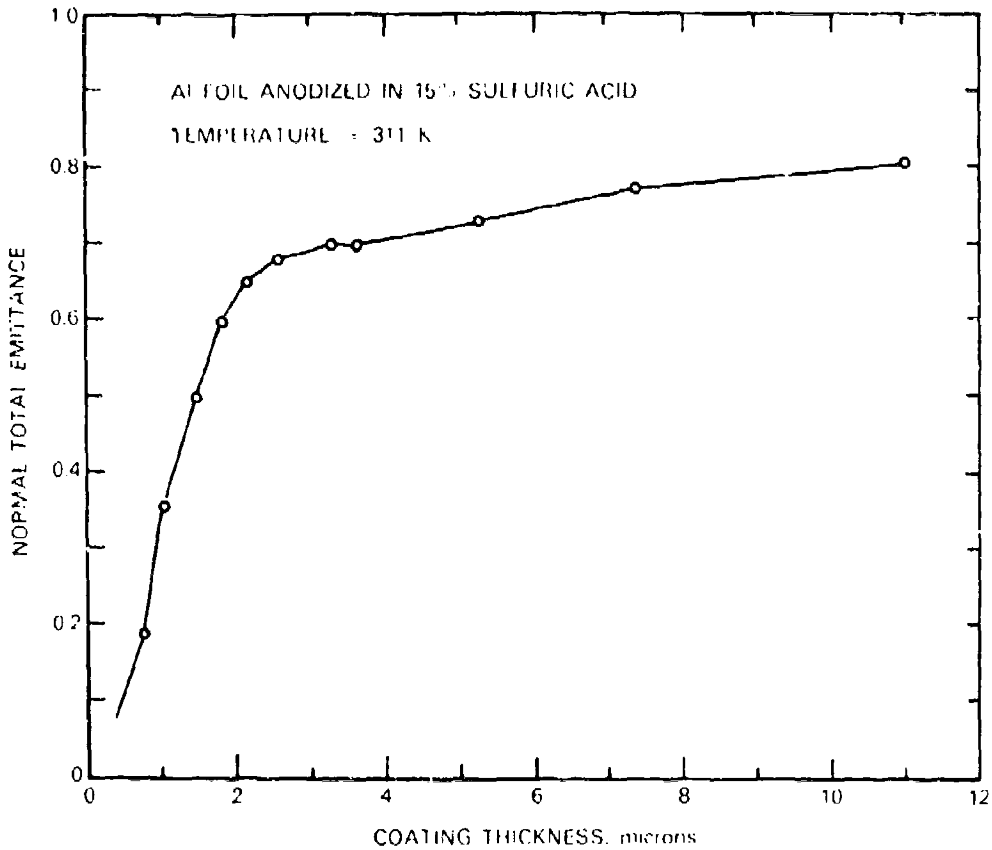

Figure 22. Total Normal Emittance of Anodized Aluminum (Ref. 5)

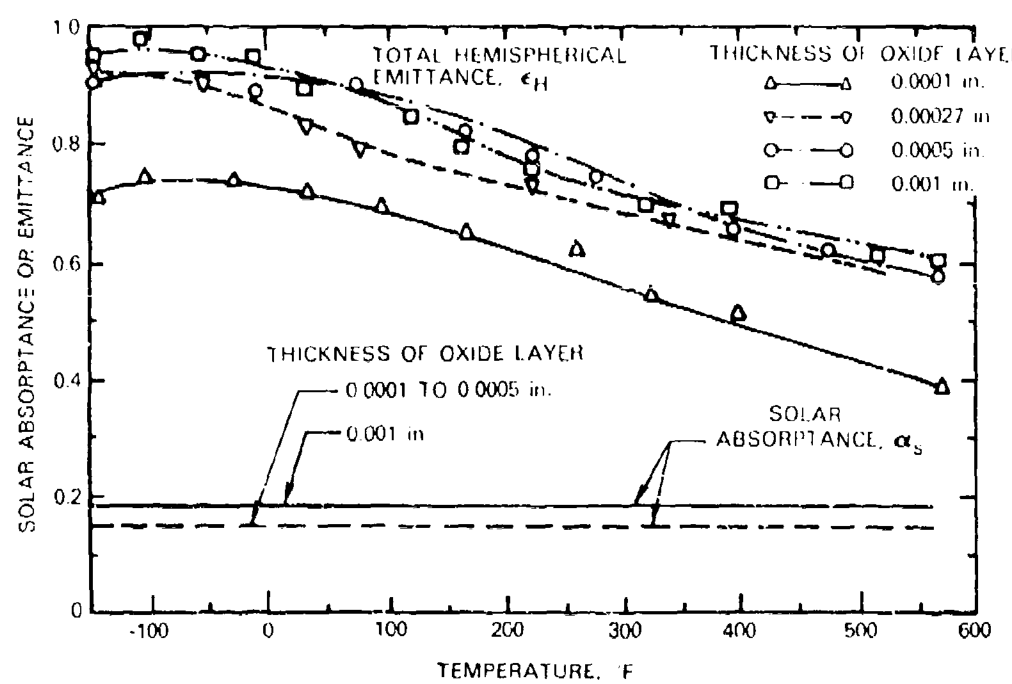

Figure 23. Total Hemispherical Emittance and Absorptance Versus Temperature of Anodized Aluminum (Ref. 16)

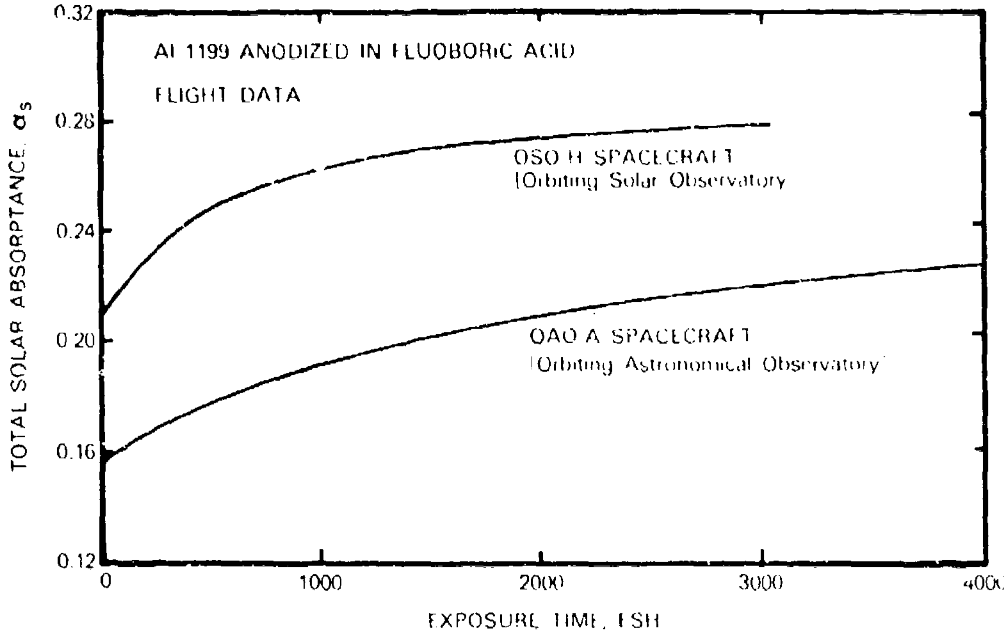

Figure 24. Solar Absorptance Degradation of Anodized Aluminum Coatings (Ref. 20)

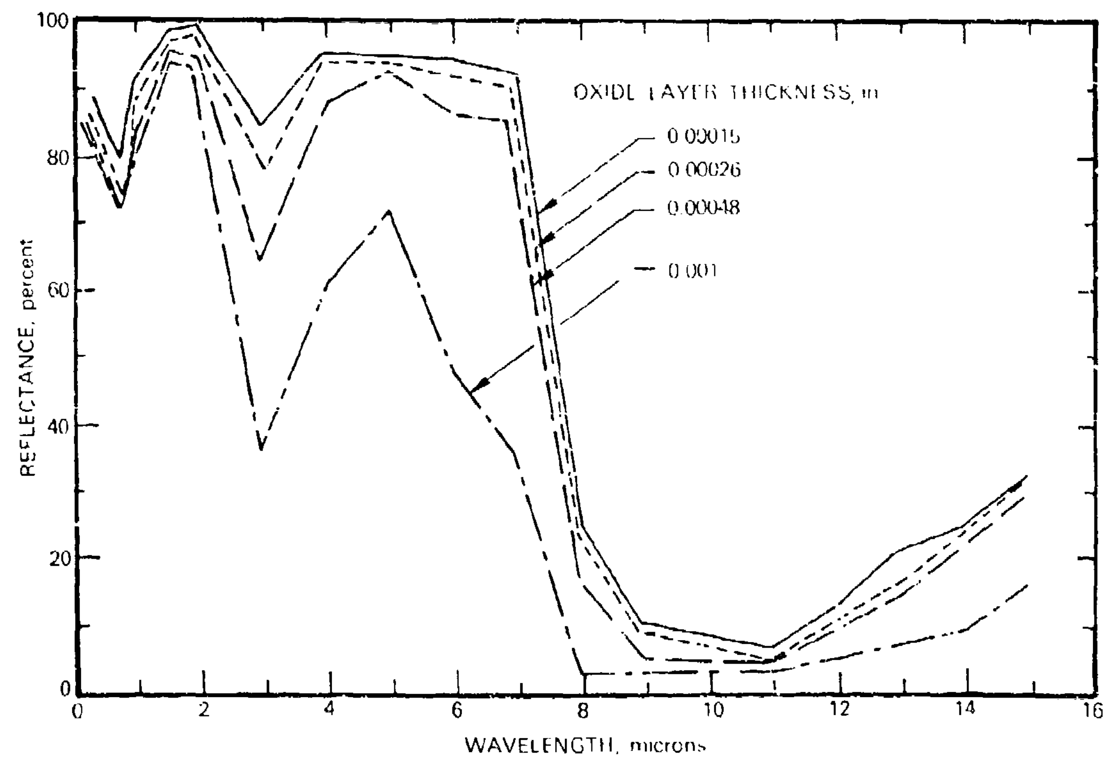

Figure 25. Spectral Reflectance of Anodized Aluminum (Ref. 21)

while being handled. These mirrors, approximately 1" × 1", are then applied to a substrate generally with a silicone adhesive such as RTV 615. For application on curved surfaces, where the rigid mirrors are not ideal, the metallic films are deposited on flexible transparent films such as fluorinated ethylene-propylene (FEP) Teflon, Kapton or Mylar.

Typical properties of rigid OSR's with 8 mil facesheets are summarized in Table 4.

Table 4. Solar Absorptance and Hemispherical Emittance of Aluminum and Silver Optical Solar Reflectors (Ref. 4)

OSR	Temperature (R)	α_s	ϵ_H	α_s/ϵ_H
Silver	260	0.050	0.744	0.067
	360	0.050	0.800	0.063
	460	0.050	0.810	0.061
Aluminum	260	0.10	0.800	0.125
	360	0.10	0.810	0.124
	460	0.10	0.800	0.124

Normal spectral reflectance of a typical OSR with silver on 6 mil fused silica is shown in Figure 26. Directional spectral emittance for an Aerojet silver OSR measured at angles from 0° to 80° is presented in Figures 27 and 28. Flexible OSR's utilizing Teflon or Mylar are produced with varying thickness which strongly affects the emittance and to some extent the solar absorptance. The spectral absorptance of silver coated Teflon is illustrated in Figure 29 for varying thickness of Teflon, based on data from Ref. 22.

[22] Linder, W., "Series Emittance Thermal Control Coatings," Proceedings of the Joint Air Force-NASA Thermal Control Working Group, 16, 17 August 1967, AFML-TR-68-198, Aug 1968.

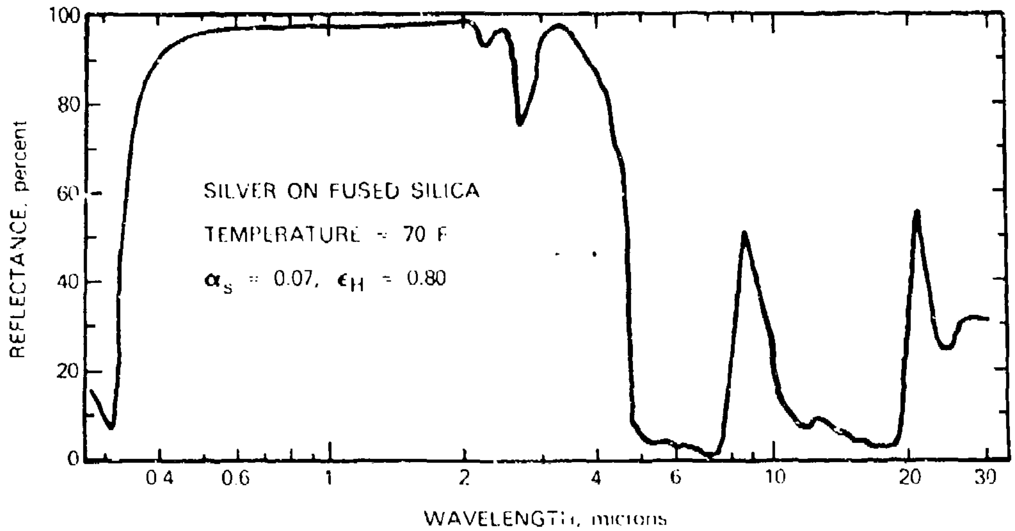

Figure 26. Normal Spectral Reflectance for a Second Surface Mirror (Ref. 6)

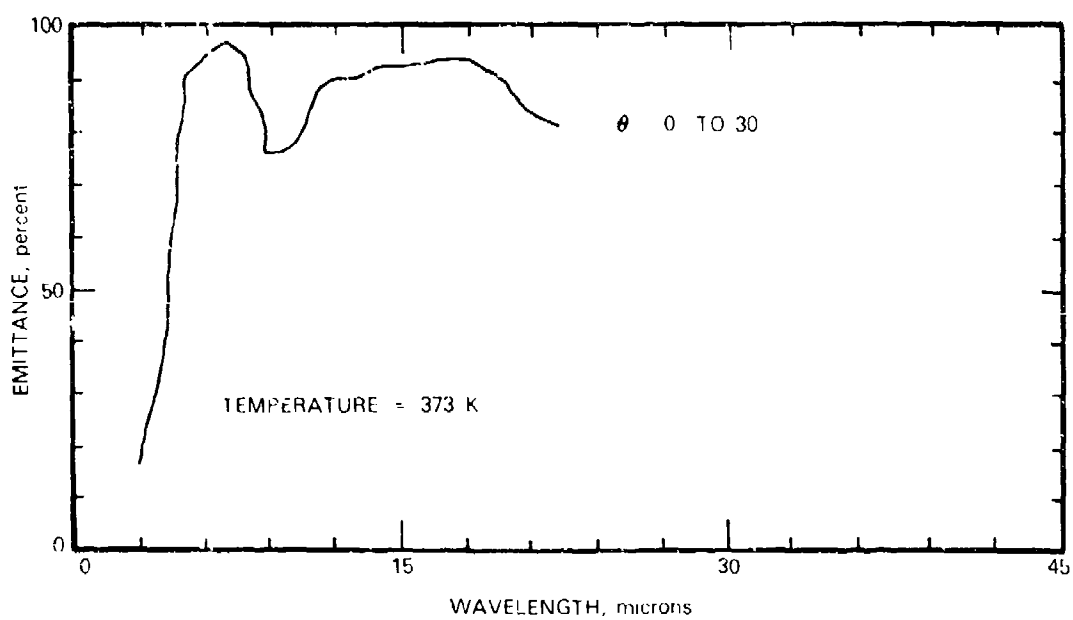

Figure 27. Directional Spectral Emittance of Aerojet Second Surface Mirror (Ref. 13)

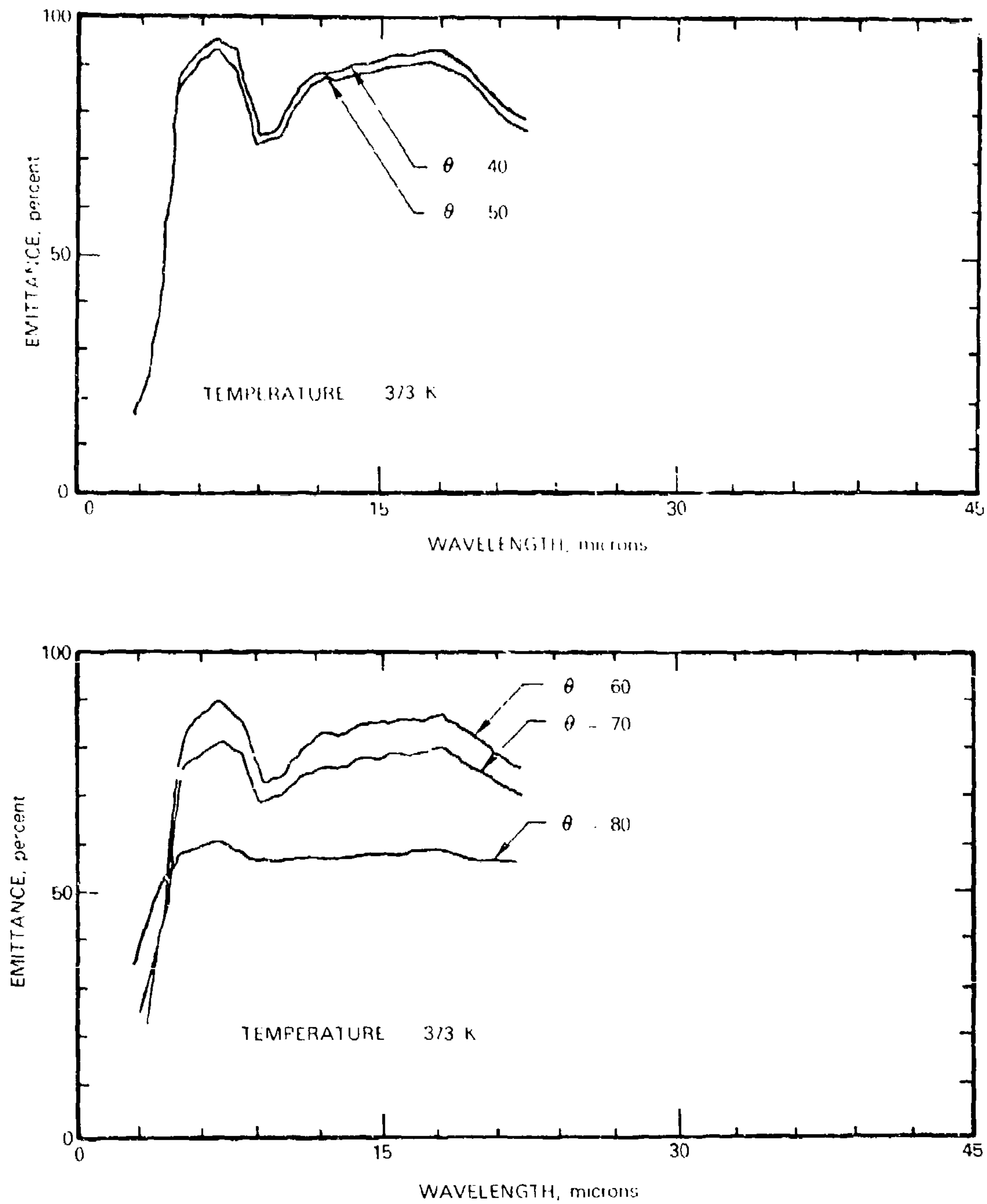

Figure 28. Directional Spectral Emittance of Aerojet Second Surface Mirror (Ref. 13)

THICKNESS mils	SOLAR ABSORPTANCE α_s	EMITTANCE ϵ_N	α_s/ϵ_N
0.5	0.055	0.422	0.13
1.0	0.059	0.515	0.11
2.0	0.059	0.675	0.09
5.0	0.090	0.802	0.11

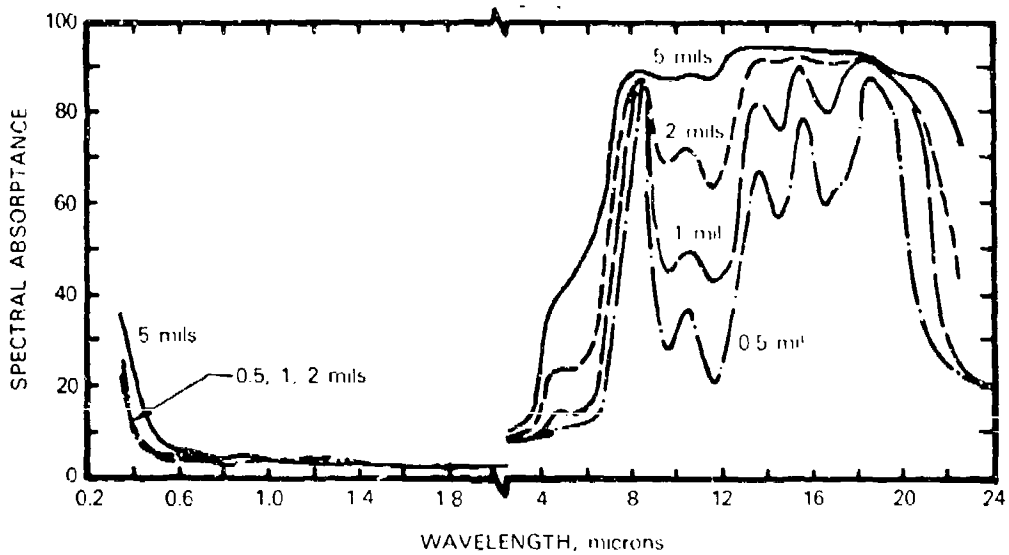

Figure 29. Spectral Absorptance of Silver Coated Teflon (Ref. 22)

The corresponding values for α_s and ϵ_N, and the ratio α_s/ϵ_N, as evaluated by the original source, are also shown. An approximate curve fit to determine the ϵ_N as a function of thickness is shown on Figure 30. Normal spectral reflectance of aluminized Mylar is presented in Figure 31. The reflectance of a number of metallized Mylar films are compared in Figure 32. The FEP Teflon films appear to be relatively stable, based on laboratory UV exposures. A 5 mil thick, silvered Teflon specimen showed no detectable degradation of α_s after 4600 hours of solar exposure in a 500 nmi orbit, based on Ref. 4. Aluminized FEP Teflon (1 mil thick) flown on the deep

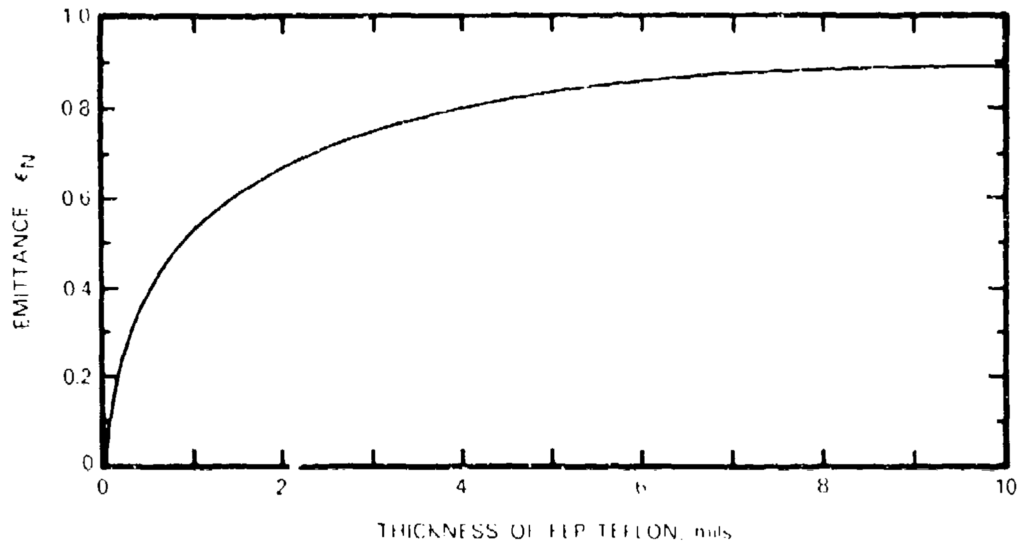

Figure 30. Normal Emittance of FEP Teflon vs Thickness (Ref. 22)

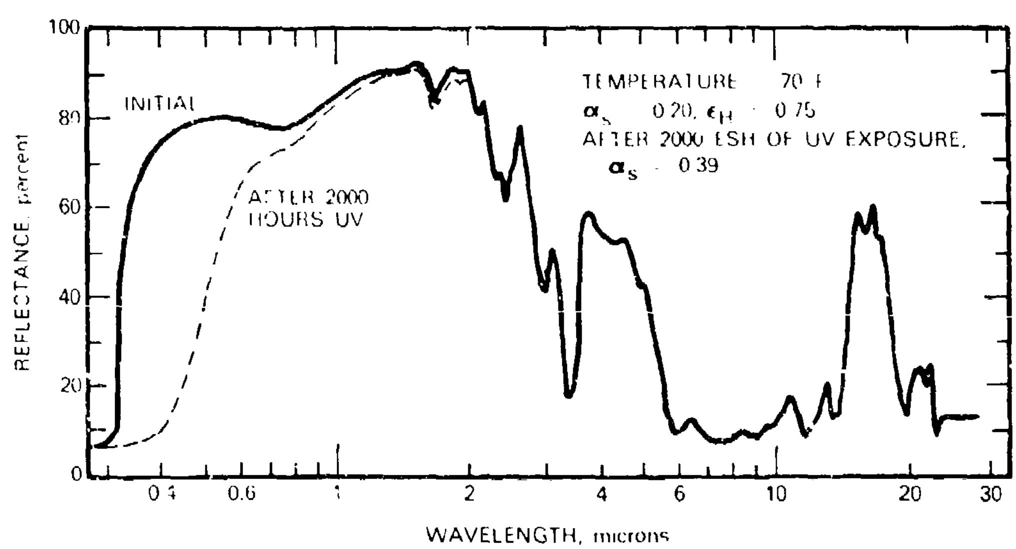

Figure 31. Normal Spectral Reflectance of Aluminized Mylar (Ref. 6)

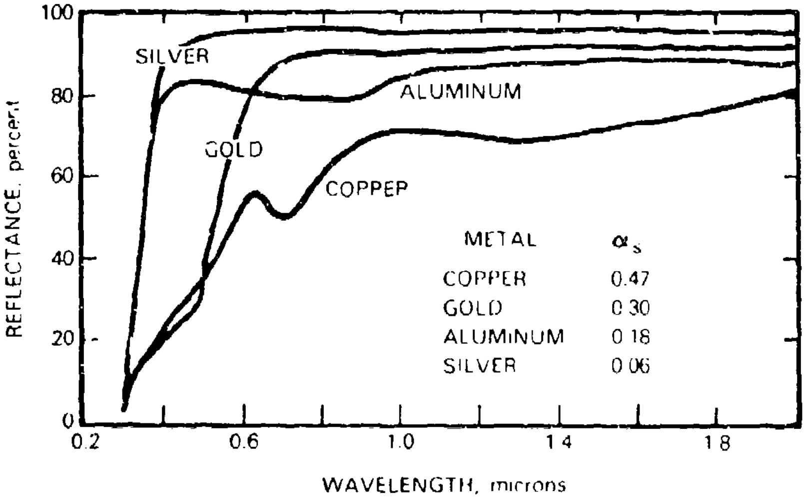

Figure 32. Reflectance of 0.5-MIL-Metallized Mylar (Ref. 22)

space Mariner V, however, showed some degradation as shown in Figure 33 from data of Ref. 15. This is apparently due to particle bombardment which is expected to far outweigh the degradation effects of UV exposure alone. Aluminized Kapton, which is used in place of aluminized Teflon where higher temperature requirements exist, is somewhat more sentitive to UV radiation. Changes in reflectance following exposure to UV radiation are shown in Figure 34.

E. SOLAR CELLS

Normal spectral reflectance for a Centralab silicon solar cell with a 6-mil fused silica facesheet is presented in Figure 35. The solar absorptance (α_s) of this specimen is 0.83. The corresponding value of ϵ_H based on a 70°F sample temperature is also 0.83.

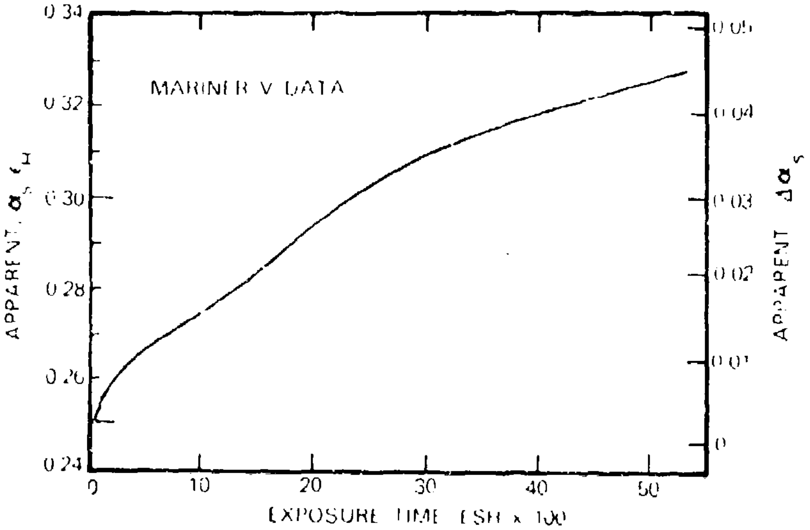

Figure 33. Apparent Degradation of Aluminized 1 MIL FEP Teflon (Ref. 15)

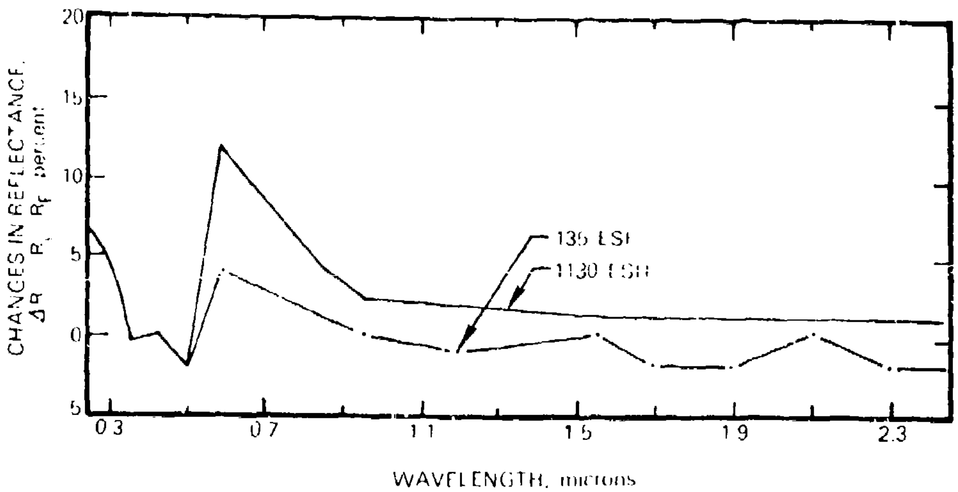

Figure 34. Spectral Reflectance Changes in Kapton H Film, Following Exposure to Ultraviolet Radiation (Ref. 4)

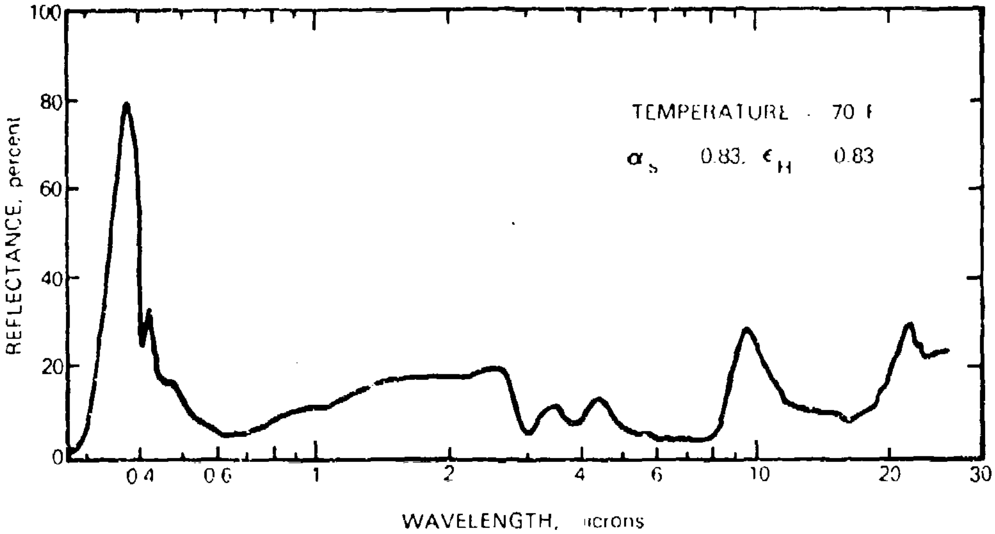

Figure 35. Normal Spectral Reflectance of Centralab Solar Cell (Ref. 6)

Directional spectral emittance for Aerojet solar cells is presented in Figures 36 and 37 measured at 373°K (100°C) and 200°K (-73°C), respectively. Cover-glass thicknesses are not specified for the Aerojet cells. Nominal cover glass thickness ordinarily ranges between 6 and 20 mils. Degradation of solar cell conversion efficiency may vary significantly with cover glass thickness and the specific orbit altitude and inclination. However, the solar absorptivity (α_S) and hemispherical emittance (ϵ_H) are relatively insensitive to cover glass thickness beyond about 6 mils and these properties would not be expected to vary significantly.

Cell conversion efficiencies may degrade an order of 20 percent over a three year period. However, since the initial conversion efficiency is on the order of 10 percent, this degradation would represent only a 2 percent increase in absorbed thermal energy by the cells. The corresponding increase in solar cell temperature would be about 3°F. Therefore, the accuracy of the data presented for solar cells should be more than sufficient for utilization in satellite infrared signature studies.

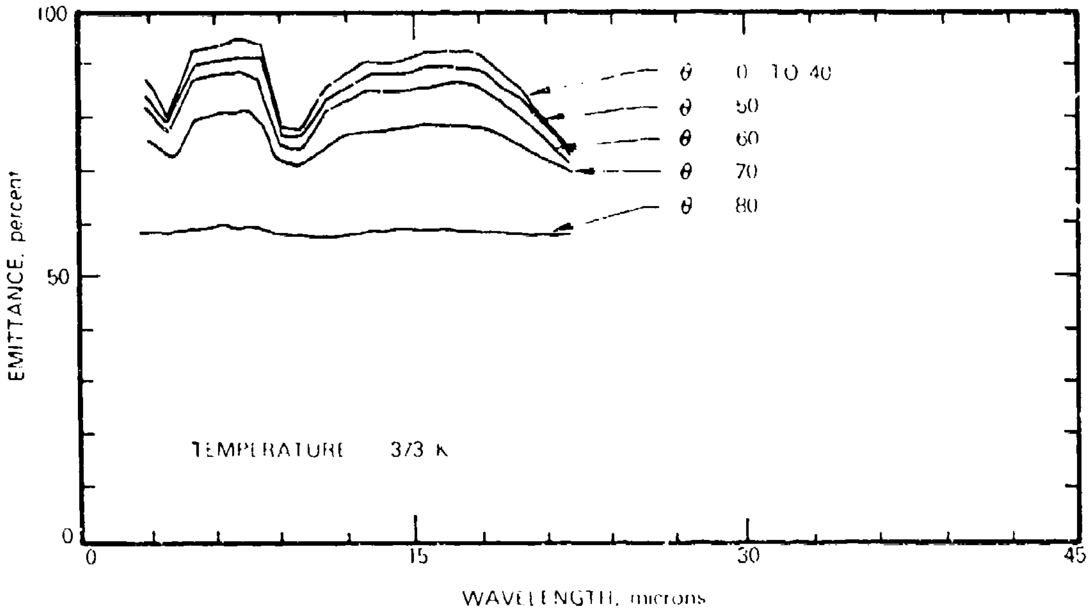

Figure 36. Directional Spectral Emittance for Aerojet Solar Cell at 373°K (Ref. 13)

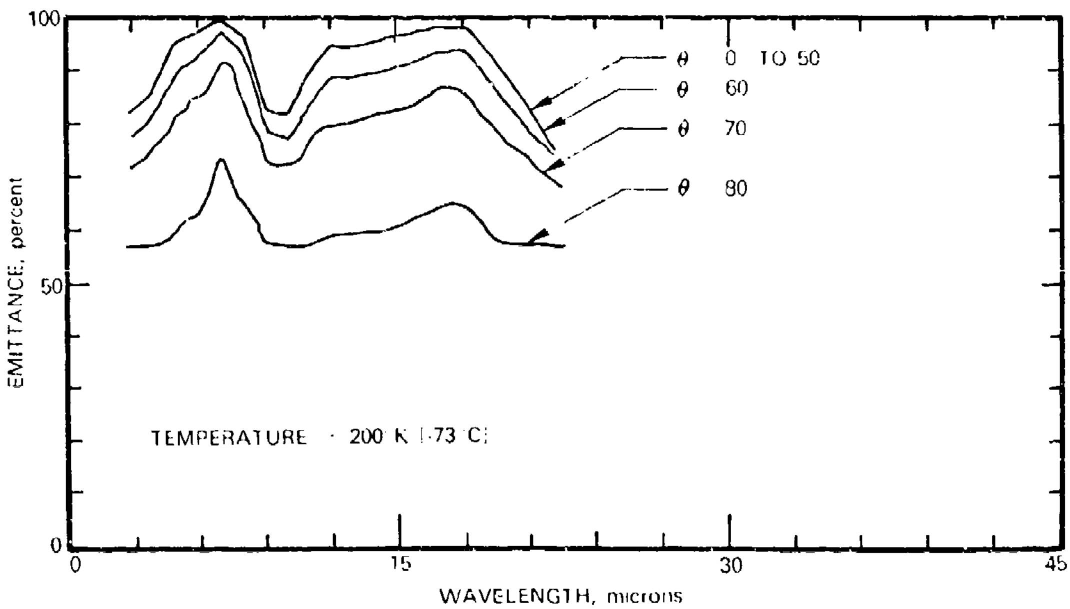

Figure 37. Directional Spectral Emittance for Aerojet Solar Cell at 200°K (Ref. 13)

REFERENCES

1. F.S. Johnson, "The Solar Constant," J. of Meteorology, Vol. II (December 1954).

2. R. Stark, Thermal Testing of Spacecraft, Report No. TOR-0172(2441-01)-4, The Aerospace Corporation, El Segundo, Calif., (September 1971).

3. R. G. Herring and T. F. Smith, "Surface Radiation Properties from Electromagnetic Theory," Int. J. Heat and Mass Transfer, Vol. 11, pp 1567-71 (1968).

4. N. J. Broadway, Radiation Effects Handbook, Section 2, Thermal Control Coatings, NASA-CR-1786. Prepared by Battelle Memorial Institute, Columbus, Ohio (June 1971)

5. Y. S. Touloukian, et al., Thermophysical Properties of Matter, Thermal Radiative Properties, Thermophysical Properties Research Center, Purdue University (1972).

6. Thermophysical Properties Measurement, Unpublished Data, TRW, Redondo Beach, Calif.

7. G. G. Gubareff, Thermal Radiation Properties Survey, 2d Ed., Honeywell Research Center, Minneapolis-Honeywell Regulator Co., Minneapolis, Minn. (1960).

8. E. Schmidt and E. Eckert, "Uber die Richtungsverteilung der Warmestrahlung," Forsch. Gebeite Ingenieorwesen, Vol. 6 (1935).

9. D. K. Edwards and I. Catton, "Radiation Characteristics of Rough and Oxidized Metals," Advances in Thermophysical Properties at Extreme Temperatures and Pressures, ASME, pp. 189-199 (1965).

10. R. E. Gaumer and L. A. McKeder, Thermal Radiative Control Surfaces for Spacecraft, LMSC-704014, Lockheed Missiles and Space Co. (March 1961).

11. A. E. Hultquist, et al., Advanced Thermal Control Materials Development, LMSC-A967871, Lockheed Missiles and Space Co. (May 1970).

12. Unpublished Data, Aerojet Electro-Systems Co., Azusa, Calif. (13 July 1973).

13. M. Pair, et al., "Optical Properties of Satellite Materials," (Draft Copy), Document No. 194100-5-F, Infrared and Optics Division, Environmental Research Institute of Michigan, Ann Arbor, Mich. (July 1973).

14. A. Eagles, General Electric Valley Forge Space Center, Philadelphia, Pa., subject: ERTS-1 Surface Coating Optical Properties Test Data, personal communication (2 Oct 1974).

15. W. F. Carroll, "Mariner V Temperature Control Reference Design, Test and Performance," Paper presented at AIAA 3rd Thermophysics Conference, JPL, Los Angeles, Calif. 24-26 June 1968.

16. J. B. Rittenhouse, et al., Space Materials Handbook, NASA SP-3025, Supp. 1 (1966).

17. R. Wallace, Lockheed Missiles and Space Co., Sunnyvale, Calif., personal communication, (10 Oct 1974).

18. G. Borson, Aerospace Corporation, Materials Science Laboratory, personal communication, (5 Sept 1974).

19. W. R. Wade and D. J. Progra, Effects of Simulated Space Environment on Thermal Radiation Properties of Selected Black Coatings, NASA TN-D-4116 (September 1967).

20. H. Fine, "An Insight into the Features of the OAC Thermal Design," ASME 73-ENAs-46, (20 Aug 1973).

21. J. H. Weaver, "Bright Anodized Coatings for Temperature Control of Space Vehicles," Plating 51 (19), pp. 1165-1172 (December 1965).

22. W. Linder, Series Emittance Thermal Control Coatings, Proceedings of the Joint Air Force-NASA Thermal Control Working Group, AFML-TR-68-198 (August 1968).

23. W. Fischer, Aerospace Corporation, personal communication (17 Nov 1974).

24. J. F. Traub, Iterative Methods for the Solution of Equations, Prentice-Hall Inc., Englewood Cliffs, N.J., 1964, pp. 221-224.

BIBLIOGRAPHY

Caldwell, C. R. and P. A. Nelson, "Thermal Control Experiments on the Lunar Orbiter Spacecraft," Prog. Astronautics and Aeronautics 21 (1969), pp. 819-52.

Childers, H. M. and J. M. Cerceo, Electron Beam Techniques for Measuring Thermophysical Properties of Materials, WADD-TR-60-190 (AD 272691).

Dunkle, R. V., "Thermal Radiation Characteristics of Surfaces," in Theory and Fundamental Research in Heat Transfer, (J. A. Clark, ed.), Pergamon Press, New York (1963).

Eckert, E. R. G. and R. M. Drake, Jr., Heat and Mass Transfer, McGraw-Hill, New York (1959).

Jakob, M., Heat Transfer, Vol. I, Wiley, New York (1949).

Langley, R. C., et al., Inorganic Films for Solar Energy Absorption, ASD-TDR-62-92, (1963) (AD424099).

Love, T. J., Radiative Heat Transfer, E. Merrill Publishing Co., Columbus, Ohio (1968).

Siegel, R. and J. R. Howell, Thermal Radiation Heat Transfer, McGraw-Hill 1973, New York (1972).

Weibelt, J. A., Engineering Radiation Heat Transfer, Holt Rinehart and Winston, New York (1966).

Wolfe, W. L., Handbook of Military Infrared Technology, Office of Naval Research, University of Michigan, U.S. Gov't. Printing Office (1965).

APPENDIX

SURFACE RADIATION PROPERTIES FROM ELECTROMAGNETIC THEORY

To obtain accurate infrared signatures of satellites in orbit, detailed spectral and directional properties are required. These surface properties are best obtained experimentally and to the extent available have been presented in this report for a selected number of materials and coatings. However, in some cases, the experimental data are incomplete or insufficient in scope or detail. In these cases, one may resort to physical models to predict surface properties, either empirically or through fundamental relations, to supplement or replace experimental data.

A method of providing this capability to obtain directional surface properties from hemispherical and normal emittance data using Fresnel relations derived from electromagnetic theory is presented herein abstracted from Ref. 23.

METHOD

Basic electromagnetic theory predicts that directional surface properties are related to the optical constants defined by the complex index of refraction, $\tilde{n}$:

$$\tilde{n} = n(1 - ik) \tag{1}$$

where n and k are refraction index and absorption index, respectively. and $i = \sqrt{-1}$

[23] W. Fischer, Aerospace Corporation, personal communication, 17 Nov. 74.

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Directional emittance of non magnetic substances for uniformly polarized, incident radiation is given in Ref. 3 by (2):

$$\epsilon(\theta) = 1 - 1/2\left[\rho_{\parallel}(\theta) + \rho_{\perp}(\theta)\right] \tag{2}$$

where

$\rho_{\parallel}(\theta)$ and $\rho_{\perp}(\theta)$ are the directional reflectances parallel and perpendicular to the plane of incidence, respectively.

and

$$\rho_{\parallel}(\theta) = \frac{(n\beta - \cos\theta)^2 + n^2\left[(1 + k^2)\alpha - \beta^2\right]}{(n\beta + \cos\theta)^2 + n^2\left[(1 + k^2)\alpha - \beta^2\right]} \tag{3}$$

and

$$\rho_{\perp}(\theta) = \frac{\left(n\gamma - \frac{\alpha}{\cos\theta}\right)^2 + n^2\left[(1 + k^2) - \gamma^2\right]}{\left(n\gamma + \frac{\alpha}{\cos\theta}\right)^2 + n^2\left[(1 + k^2) - \gamma^2\right]} \tag{4}$$

θ is the polar angle of incidence relative to the surface normal and α, β, and γ are defined by:

$$\alpha^2 = \left[1 + \left(\frac{\sin^2\theta}{n^2(1 + k^2)}\right)\right]^2 - \frac{4}{(1 + k^2)}\left[\frac{\sin^2\theta}{n^2(1 + k^2)}\right] \tag{5}$$

$$\beta^2 = \frac{(1 + k^2)}{2}\left[\left(\frac{1 - k^2}{1 + k^2}\right) - \left(\frac{\sin^2\theta}{n^2(1 + k^2)}\right) + \alpha\right] \tag{6}$$

$$\gamma = \frac{(1 - k^2)}{(1 + k^2)} \beta + \frac{2k}{(1 + k^2)} \left[(1 + k^2) \alpha - \beta^2\right]^{1/2} \tag{7}$$

Normal emittance is obtained for the case where $\theta = 0$ and is given by

$$\epsilon_N = \frac{4n}{(n + 1)^2 + n^2 k^2} \tag{8}$$

Hemispherical emittance is calculated by integrating directional emittance over half space.

$$\epsilon_H = \int_0^1 \epsilon(\theta) \, d(\sin^2 \theta) \tag{9}$$

Often only hemispherical and normal emittance data are presented in tables of experimental data. To obtain values for optical constants, n and k, which correspond to values of ϵ_H and ϵ_N, Eqn (8) and Eqn (9) must be solved simultaneously. Solution to these expressions is a formidable task and numerical techniques are employed to obtain values for n and k.

For perfect dielectrics, absorption index, k, is zero. Thus either refraction index, n, or hemispherical emittance, ϵ_H, or normal emittance ϵ_N, will uniquely define dielectric surface properties.

Expressions for normal emittance and hemispherical emittance simplify to

$$\epsilon_N = \frac{4n}{(n + 1)^2} \tag{10}$$

and

$$\epsilon_H = 1/2 - \frac{(3n+1)(n-1)}{6(n+1)^2} - \frac{n^2(n^2-1)^2}{(n^2+1)^3} \ln\left(\frac{n-1}{n+1}\right)$$

$$+ \frac{2n^3(n^2+2n-1)}{(n^2+1)(n^4-1)} - \frac{8n^4(n^4+1)}{(n^2+1)(n^4-1)^2} \ln(n) \qquad (11)$$

Often only hemispherical emittance or normal emittance values are provided for dielectrics. If normal emittance is provided, a simple solution for refraction index, n, results. Conversely, the solution for refractive index, n, becomes more involved when only hemispherical emittance is presented. Using the Newton Raphson method (Ref. 24) a value for n may be quickly obtained.

$$n_{m+1} = n_m - \frac{(\epsilon_H - \epsilon_{H_m})}{\left.\frac{\partial \epsilon_H}{\partial n}\right|_m}$$

If experimental data are not available to provide spectral or total emittance property values, empirical models, semi-empirical models, or classical mechanical models may be employed. Selection of an appropriate model to evaluate surface properties often depends upon the spectral range over which data are required or availability of model parameter values. Care should be exercised to apply models over applicable spectral and temperature ranges and to use the most accurate source of data available.

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[24] Traub, J. F., Iterative Methods for the Solution of Equations, Prentice-Hall Inc., Englewood Cliffs, N. J., 1964, pp. 221-224.

ACRONYMS AND SYMBOLS

Al	symbol for the element aluminum
ATS	Applications Technology Satellite
ERTS	Earth Resources Technology Satellite
ESH	equivalent sun hours
e/cm^2	integrated exposure of electrons per square centimeter of surface area
FEP	fluorinated ethylene propylene
OAO	Orbiting Astronomical Observatory
OSO	Orbiting Solar Observatory
OSR	optical solar reflector
Sn	symbol for the element tin
T	temperature, the scale as defined
Ti	symbol for the element titanium
V	symbol for the element vanadium
α	absorptance, the ratio of the absorbed radiant flux to the incident flux
ϵ	emittance, ratio of the radiant emission of a surface to that emitted by a blackbody radiator and the same temperature and wavelength
ρ	reflectance, ratio of reflected radiant flux to the incident flux
θ, θ'	the angle measured from the normal to a surface to describe the directional location of the viewer and incident ray, respectively
ϕ	the azimuth angle to describe the orientation of the viewer with respect to the incident ray as measured in the plane of the surface

Subscripts

N	conditions for incidence or viewing through an angle θ that is essentially normal to the surface
H	conditions for incidence or viewing over a hemispherical region, i.e., 2π steradians of the surface
s	Having the wavelength distribution of the sun. When used in conjunction with α the spectral absorptance of the specimen has been integrated over the wavelength distribution of the sun.
T	signifies total. When used in conjunction with α or ϵ it represents integration over all wavelengths from 0 to infinity
λ	wavelength or a narrow band of wavelengths
Θ	the angle measured from the normal to the surface defining the geometric conditions of viewing